The building blocks of battery technology

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The Building Blocks of Battery Technology: Using Modified Tower Block Game Sets to Explain and Aid the Understanding of Rechargeable Li-Ion Batteries

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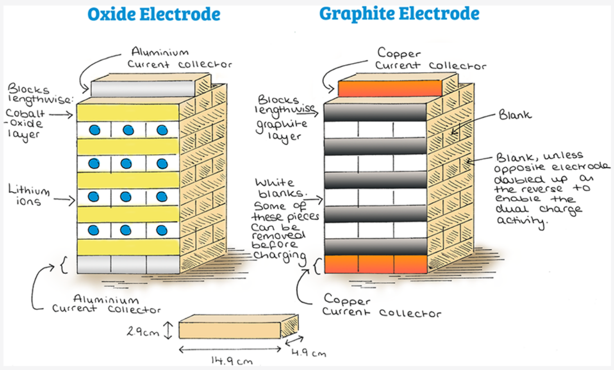
ABSTRACT: While Li-ion batteries are abundant in everyday life from smart phones to electric vehicles, there are a lack of educational resources that can explain their operation, particularly their rechargeable nature. It is also important that any such resource can be understood by a wide range of age groups and backgrounds. To this end, we describe how modified tower block games sets, such as Jenga, can be used to explain the operation of Li-ion batteries. The sets can also be utilized to explain more advanced topics such as battery degradation and challenges with charging these batteries at high rates. In order to make the resource more inclusive, we also illustrate modifications to prepare tactile tower block sets, so that the activity is also suitable for blind and partially sighted students. Feedback from a range of groups supports the conclusion that the tower block sets are a useful tool to explain Li-ion battery concepts.



KEYWORDS: *Hands-On Learning/Manipulatives, Demonstrations, Electrochemistry, Oxidation/Reduction, Oxidation State, Solid State Chemistry, Materials Science*

Li-ion batteries are everywhere, from smart phones to laptops, and in more recent times in electric vehicles due to targets of reducing greenhouse gas emissions to mitigate the effect on climate change. With a technology so readily accessible and the continuation of research efforts (30 years on from the commercialization of the initial cell[1] and following the award of the 2019 Nobel Prize for Chemistry to Akira Yoshino, M. Stanley Whittingham, and John B. Goodenough) from the development of novel materials to end-of-life recycling efforts,[2] such rechargeable batteries are still, more than ever, a hot topic.

Therefore, it is paramount to be able to explain the basics of operation not only to the relevant undergraduate student body, but also to schools and the general public, especially with the ease of accessibility of these consumer products and developments in related and relevant environmental policy.

The key to understanding battery operation relies on understanding the redox processes and the electrochemistry at play. When teaching this area, specifically the electrochemistry, multiple applications can be tied to these fundamental principles;[3] however, this topic is more than often associated with being a troublesome area to teach.[4] This issue is attributed to taught misconceptions which are formed either from misinterpretation or overgeneralization to inappropriate situations.[5] Multiple surveys to assess the drawbacks and misconceptions for this area have been conducted, in addition to the use of a cognitive conflict approach, for both teachers[6] and students,[5,7] respectively, in efforts to understand how to improve the teaching of this area.

To support learning and to be engaging, hands-on demonstrations are often used. The most commonly used activity employs lemon-/potato-electrolyte batteries,[8] which are useful for introducing the concept of electrode potentials, electrical circuits, and a non-rechargeable battery. The basics of this demonstration involve piercing a zinc-containing nail and a copper coin into either a lemon or a potato. The metals are the electrodes in the circuit, and the lemon/potato acts as the electrolyte. The metals are connected to a voltmeter. This demonstration and other approaches are tactile and can be made visually and acoustically stimulating, with a connection to a music birthday card[8] or with a connected LED[9] or a clock.[10] In addition, quite often these demonstrations make use of classroom-based tools or use available household products.[11] Hence, these activities in general are suited for a

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wide range of students, including those who are either visually impaired or deaf.[8]

Although these are good hands-on activities to introduce key aspects of batteries, these demonstrations cannot explain how rechargeable batteries work and, additionally, often lead to a misconception that the lemon or the potato is the powerhouse behind the circuit. Within the literature, efforts to explain and elaborate on the chemistry of the Li-ion battery appear to be limited to a degree level.[12−15] Of the limited resources in a different medium to the degree classroom and laboratory-based practical, a recently published video titled "Lithium Shuffle—Battery Operation" explores the basic setup of these batteries before making use of a human-sized Li-ion battery to show the mobility of the ions involved.[16,17]

The lack of demonstrations to explain Li-ion batteries has been our motivation to design a suitable activity in using tower block sets, such as Jenga, which can complement the non-rechargeable demonstrations. The archetypal Li-ion battery with electrode materials $LiCoO_2$−graphite is a layered system, and hence, the stacking of blocks in a normal tower block game makes this traditional set ideal for customization into the appearance of this battery setup.

This is not the first instance of this tower block game being used in an educational setting. They have been used to explore risk management concepts to senior nursing students whereby the student had to identify risks to patients without the tower toppling over.[18] In addition, it has been used for teaching institutional oppression, whereby the game is played normally but rules are introduced to make the game play increasingly difficult.[19] Both authors of these studies comment on how the use of the tower block game acts to promote engaging learning and reinforce/fortify the students' new understanding. A more recent case study involving a tower block game for educational purposes has been the "Scientific Scissors: Genetic Jenga" game, whereby laboratory tongs are used to remove or replace the blocks representing genetic code, and this allows resultant discussion of how genes are connected and how displacements can affect the surrounding genes.[20]

A rechargeable Li-ion battery consists of two electrodes, such as a layered lithium transition metal oxide electrode ($LiCoO_2$, or Ni, Mn, Al doped analogues) and a graphite electrode. The electrodes are separated with an electrolyte. A simplified schematic is shown in Figure 1. On charging, the lithium ions traverse via the electrolyte, from the oxide electrode to the graphite electrode. An electron will move via

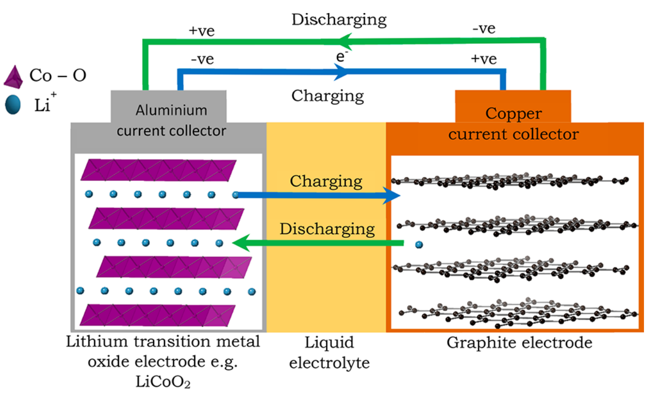

Figure 1. Diagram depicting the charge mobility on charging and discharging between the two electrodes.

the current collectors through an external circuit. On discharging, the reverse process will occur, and hence, the electron will do "work" and power our application.

The redox processes in the discharging diagram, i.e., when our battery is powering a device, can be described with the following equations, eqs 1 and 2, such that the (negative) graphite electrode is being oxidized (losing an electron) and the (positive) oxide electrode is being reduced (gaining the electron). Through this redox process, the Li-ion from the graphite will migrate through the electrolyte back into the oxide electrode, while the electron traverses the external circuit powering the device.

Negative Electrode—Oxidation

$$CLi_x \rightarrow C + xLi^+ + xe^- \quad (1)$$

Positive Electrode—Reduction

$$xLi^+ + Li_{1-x}CoO_2 + xe^- \rightarrow LiCoO_2 \quad (2)$$

Earlier batteries made use of lithium metal (Li) as the negative electrode, and these, eqs 3 and 4, are given in the AQA Chemistry A-level specification.[21,22] However, in a real battery, not all the Li can be removed from $LiCoO_2$ (hence, it should be more accurately represented with eqs 1 and 2). Due to the high cost of cobalt, current strategies are to reduce the Co content of the oxide electrode, with the most widely used current systems being mixed Ni/Mn/Co ($LiNi_{1-x-y}Mn_xCo_yO_2$, NMC) or Ni/Co/Al ($LiNi_{1-x-y}Co_xAl_yO_2$, NCA) materials, which have similar layered structures.

Negative Electrode—Oxidation

$$Li \rightarrow Li^+ + e^- \quad (3)$$

Positive Electrode—Reduction

$$Li^+ + CoO_2 + e^- \rightarrow Li^+[CoO_2]^- \quad (4)$$

■ ACTIVITY

We purchased two tower block sets, with each set consisting of 58 blocks, and before use, we set up each of the towers which reached a height of 0.6 m.

One set was designated to be the lithium cobalt oxide ($LiCoO_2$) material (oxide electrode; cathode; positive electrode) and the second as the graphite electrode (anode; negative electrode). Note that battery chemists name the electrodes (cathode/anode) based on the *processes occurring on discharging*; from here on, the positive (cathode) and negative (anode) will be referred to what they are on discharge and be simplified to oxide and graphite electrodes, respectively.

For our initial two sets, we opted to paint the sets as follows: cobalt oxide layer/purple and red spheres (16), graphite layer/gradient gray (8), lithium/blue dots (42), white blanks (24), copper/orange (1), aluminum/gray (4), and orange/gray dual side (1) with additional spares of 16 blocks (7 blanks, 1 orange, 8 lithium). The two tower sets at their full height are shown in Figure 2 without the additional spare blocks.

The two tower block game sets in this form allowed us to show intercalation processes that occur on charging through the removal of the lithium-ion blocks between the longitudinal cobalt oxide blocks and insertion of them between the longitudinal layers of the graphite in our second tower set

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Figure 2. Two of the battery towers set up with the oxide electrode (left) and graphite electrode (right).

(Figure 3). The reverse motion with the removal of the lithium from the graphite electrode back to the oxide electrode shows the processes that occur on discharging.

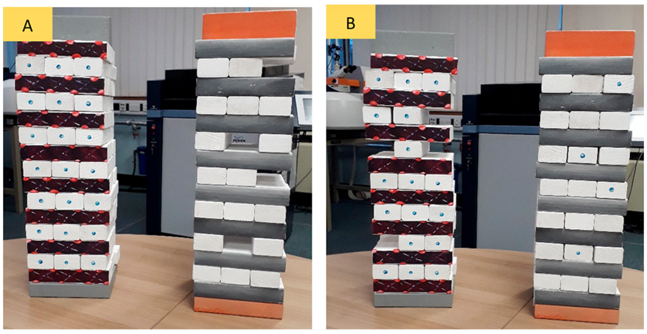

Figure 3. Painted tower block game sets with the electrodes set up. (A) The graphite electrode shows vacancies where the lithium blocks can be inserted, as shown in part B on charging from the oxide electrode.

One aspect of battery chemistry is that it is not possible to remove all the Li from between the CoO_2 layers. Typically, only half of the lithium ions present in $LiCoO_2$ can be removed, which we can visually show with the tower block sets. When running the demonstration of charging, participants select specific lithium-ion blocks, but never 3 lithium ions in one row; when students are asked why, they explained that this is to prevent the tower from collapsing. This is synonymous with this material, whereby overcharging (removing more than $x = 0.5$ Li from $Li_{1-x}CoO_2$) can result in the breakdown of the material, as CoO_2 is an unstable intermediate and there is a resultant oxygen release, which can oxidize the electrolyte and result in the danger of a battery fire.

In addition, the battery tower block game sets can show the capacity fade concept (why the performance of the battery reduces over continued use) due to the degradation of the battery, through showing how the blocks become slightly displaced (Figure 4) when removing and inserting the lithium blocks into the electrodes, illustrating distortions in the structure on removal/reinsertion of lithium.

With our original graphite electrode set, on the reverse side, the blocks were painted in the same way as those for our oxide electrode. Through turning our graphite set round by 180° and placing it adjacent to our initial oxide electrode, the two oxide electrodes (Figure 5) could be used to show what happens

Figure 4. Oxide electrode tower block set showing that cobalt oxide layers have become displaced through the (de)intercalation of the lithium during cycle, thus showing degradation.

Figure 5. (A) Painting some of the blanks in the graphite layer to be like the cobalt oxide layer in the graphite electrode allowed us to have two oxide electrode sets. The two oxide electrode towers can be used to show the differing rates of charges with volunteers: slow charge (B) and fast charge (C) which has resulted in structure collapse.

with the varying rates of charges applied (i.e., fast or slow removal of the lithium ions). In running this activity, two students were invited to participate, with one student operating at slow charge with slow removal of the lithium blocks, while the other student would be representing fast charge and would remove the lithium blocks as fast as they could; this invariably leads to the eventuality of structure collapse, as the displacement of the blocks becomes more severe.

■ TACTILE BATTERY TOWER BLOCK SET

The initial painted tower block sets were further developed to enable the activity to be more inclusive, nominally for students who are blind or partially sighted. Therefore, this set needs to have a good contrast in colors, in addition to having distinct shapes and textures. For this version, one tower set was purchased and divided in two, with each tower having a lithium cobalt oxide electrode face and a graphite electrode on the rear to make multiple use of the sets (Figure 6A). For the oxide electrode, the lithium ions are represented by blue painted wooden buttons and the cobalt oxide layers with purple glitter

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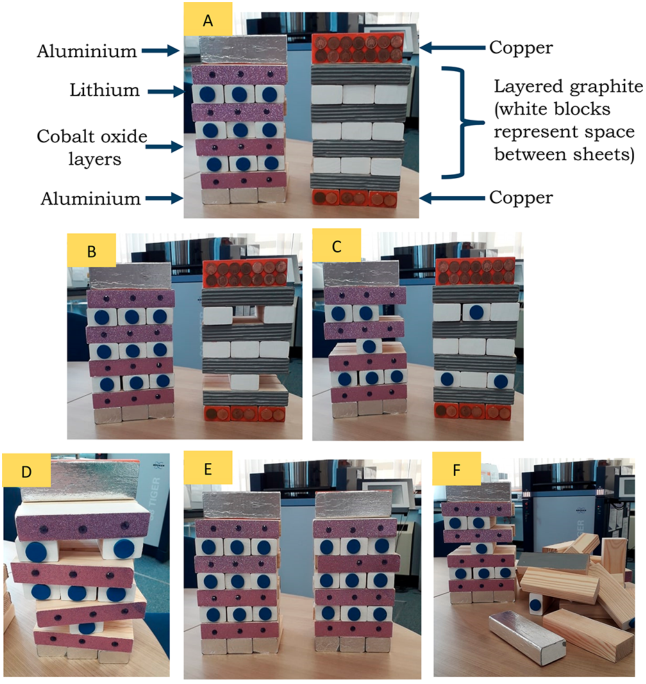

Figure 6. (A) Tactile tower block electrodes' setup (note that each tower has the opposite electrode on the reverse). (B) Presentation of vacancies where the lithium blocks can be inserted, as shown in part C. Panel D shows how the blocks do not remain in the exact positions, and hence, degradation can be shown. (E) Two oxide electrodes presented in preparation of the rate-charge activity. (F) The aftermath of the rate-charge activity; the left tower had a slow charge applied, while the right tower has collapsed from charging too fast, i.e., removal of the lithium blocks too fast.

paper with embossed plastic gems. The graphite electrode was produced with painted gray cardboard albeit without the top layer, to leave a ridged texture akin to the layered structure of this material. The aluminum current collector was decorated with aluminum foil, while the copper current collector was painted orange and had a 1 pence piece affixed to the surface. The total number of pieces represented is as follows: cobalt oxide layers (10), graphite layers (10), lithium pieces on one end with a white blank on the opposite end (24), white blanks (8), orange copper on one square face and aluminum foil on the opposite end (6), and longitudinal 50/50 orange copper/aluminum foil (2).

As with the painted tower block set discussed previously, the different activities can be visualized with the tactile equivalent. To allow the lithium-ion insertion path to be clearer, vacancies in the graphite electrode can be removed beforehand, as shown in Figure 6B, before charging (Figure 6C). Degradation (Figure 6D) and charging rates (Figure 6F) can also be demonstrated, as previously mentioned with our initial painted set. Producing a demonstration that is tactile benefits all learners, not just students who are blind or partially sighted.

■ FEEDBACK

The demonstration has been used with multiple age groups since March 2019, from secondary school students having an introduction to rechargeable batteries to university level undergraduates receiving the demonstration to reinforce learning and key concepts for this type of battery, as well as to the general public at a range of museums and other events. From these earlier events, we received a range of positive comments on sticky notes as feedback. In order to assess the usefulness of this activity in more detail, a survey was handed out before and after the battery tower blocks demonstrations, during a week period in January 2020. The first two questions asked for words associated with "Rechargeable batteries" and "Li-ion batteries". The following two questions (nos. 3 and 4) in the pre-demonstration survey were presented with choices on the Likert scale with "I am confident in explaining which electrode is which in a $LiCoO_2$−graphite cell for a Li-ion battery" and "I am confident in explaining how Li-ion batteries operate", with tick box options of "not at all", "a little", "not sure", "some", and "greatly". All of these initial questions were asked again after the use of the battery tower blocks demonstration in a post activity survey with the additional question of "The battery tower blocks are a useful prop in explaining how Li-ion batteries operate" with a final open feedback box on how the activity could be improved in understanding.

Responses were gathered from year 3 chemistry undergraduate students (n = 13) who were receiving an introductory lecture to rechargeable batteries. The survey was then open to other chemistry undergraduates, who came along to a separate session (n = 16). Responses were then collected from year 9 to year 11 secondary school children before an energy-based demonstration lecture, where the battery tower blocks were used to explain the operation of Li- (and Na-) ion batteries (n = 49). Finally, the painted and tactile tower block game sets

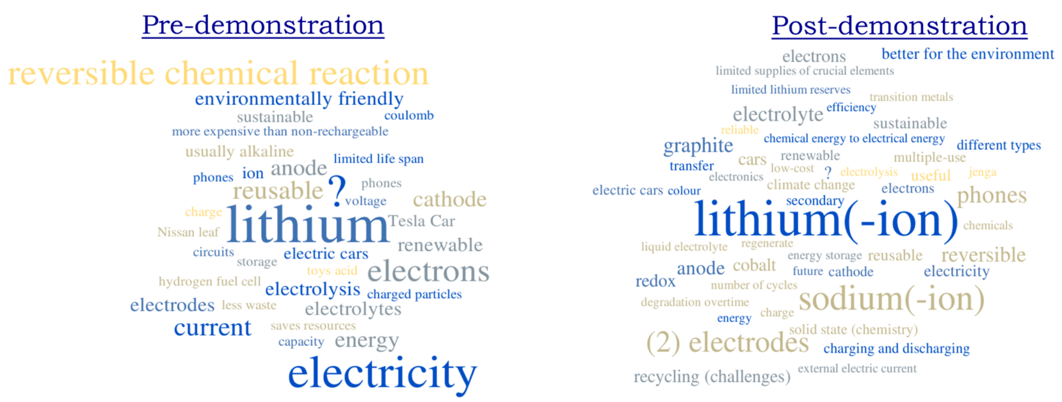

Figure 7. Generated word chart from collected responses from year 9−11 school children pre- and postdemonstration for the question of 'words associated with "Rechargeable batteries"'.

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were shown to a small group of adults who specialize in public engagement and work with children with special educational needs (n = 3).

The following section will consider these responses, with the generation of the word plots considering the frequency of associated words for the first question and tabulated answers for questions 3−5.

The year 9−11 school children word chart responses are presented for question 1 in Figure 7, with pre- and post-demonstration answers. These responses are shown in particular, due to this group being the larger cohort and the least experienced in terms of chemistry. The word chart responses for question 2 for this group, along with the university students' answers for both initial questions are provided in the Supporting Information. The initial responses to the word associated with "Rechargeable batteries" appear to be words connected to electricity and the topic's physical quantities, in addition to the name of applications of where this type of battery can be found, i.e., phones and electric vehicles.

The pre-demonstration survey answers for question 2 of words associated with Li-ion batteries, again, had applications stated; however, electrode terminology was stated, i.e., cathode and anode. The post-demonstration survey answers for this question are presented in the Supporting Information.

The post-demonstration responses for both questions appear to consider more technical information on what these batteries consist of chemically and greater concerns for the environment.

If no responses were given to either of the associated word questions, a question mark was counted as that response. The frequency of an unsure answer reduced after the post-demonstration. Note that, in the energy lecture, Na-ion batteries were mentioned, and hence, this is why some students have written this as an answer.

The Likert responses from all groups, university students, adults, and year 9−11 school children, pre- and post-demonstration, will now be considered collectively for the following questions within Table 1.

- Question 3: I am confident in explaining which electrode is which in a $LiCoO_2$−graphite cell for a Li-ion battery.
- Question 4: I am confident in explaining how Li-ion batteries operate.
- Question 5: The battery tower block game is a useful prop in explaining how Li-ion batteries operate.

The general trend for questions 3 and 4 in the post-activity survey all show a positive response of students finding they would be more confident in answering these questions. The responses from the adult group seem to be a small improvement from the demonstration, but this could be due to this group being a small sample size, as well as to not having a chemical background and to receiving only a 10 min overview (since this was done in a session, where a range of tactile chemistry resources were being discussed), thus requiring more time to grasp the concept.

The responses on whether the battery tower blocks demonstration is useful for explaining Li-ion batteries operation all had extremely positive responses, with no one stating it was not useful at all. The university students appear to have found the battery tower block sets the most useful, but this may be due to the fact that battery science is a university module. Overall, the results from these surveys, and general feedback from our prior use at a range of events, support the

Table 1. Responses from the Three Different Audiences[a]

		Responses				
Audience	Question	Not at All	A Little	Not Sure	Some	Greatly
University students	3 (pre)	8	4	8	8	1
	3 (post)		1		17	11
	4 (pre)	5	8	4	11	1
	4 (post)		1		14	14
	5 (post)				2	27
Adults	3 (pre)	3				
	3 (post)	1	1		1	
	4 (pre)	3				
	4 (post)		2		1	
	5 (post)		1		1	1
Year 9−11 school children	3 (pre)	41	2	4	2	
	3 (post)	3	15	4	25	2
	4 (pre)	26	15	3	5	
	4 (post)		9	2	32	6
	5 (post)		2	2	21	24

[a]University students, adults, and year 9−11 school children in response to questions 3, 4 and 5, with the pre- and post-activity survey results recorded on the Likert scale.

conclusion that the battery tower block game is a useful tool to explain Li-ion battery concepts.

More in-depth written feedback was received from some students within the undergraduate group covering how the battery tower block game sets can support their learning from an assessment standpoint. The students comments centered around the demonstration offering a clear visualization of the structural chemistry of the electrodes, how the demonstration helped support the topic of redox reactions and from the application viewpoint, the rechargeable nature of these batteries, and how they degrade with time.

From a structural point of view, the students commented that the tower block set was useful in showing "a visual differentiation of the [electrodes] that isn't always as clear from just diagrams", in addition to commenting that the battery tower block sets do "an excellent job of showing the distinct layers present in the electrodes" and show that "lithium exists in different layers to the cobalt oxide in one electrode and the graphite in another". This student went on further to comment how the 'white "blanks" between the graphite layers [were] really useful in defining the layers and showing exactly where and how the lithium ions intercalate'. Another student commented on the movement of the lithium ions which "helped [the] understanding of how a lithium-ion battery works" and said that "it was clear that not all lithium ions from one layer could be removed as then the lithium cobalt oxide would not be able to retain its structure".

In terms of the topics, which the demonstration can support, redox reactions and (electrochemical) potentials were cited. "Although the activity itself didn't explicitly detail the reduction potentials of the processes", when put "into the context of charging and discharging an electrical device, it became clear where work was being done". In addition, another student commented that "an understanding of the redox processes alone means that these scenarios are a bit difficult to visualize effectively and that's where the demo has its real strength; a visual representation which accurately

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mirrors concepts that are potentially difficult to grasp otherwise".

In terms of explaining battery characteristics with operation, rates of charges, and degradation, the students praised the demonstration highly for the ease of visualizing these different aspects. "This is a really useful tool for showing lithium charge and discharge, which is a really important concept in the batteries course I have taken this year. I also like how this introduces some important aspects of battery chemistry such as high rate of charge (balancing a fast rate for applications such as charging cars/portables quickly vs. avoiding collapse of the structure when too many lithium ions are removed at once)". "The demonstration involving many charge/discharge cycles is useful in demonstrating that batteries are rechargeable but that their structure will degrade over time" and highlights the "down fall of fast charge cycles and the dangers of over-extraction of Li-ions which damage the structure of electrodes".

Connecting the tower block set activities to real life observations when explaining these mechanisms to students can reinforce learning, such that one student drew a connection by commenting that the "degradation of the cobalt structure happens due to charging and discharging of the lithium ions, causing the cobalt oxide to become degraded and this is the reason the battery on my phone worsens with the more I charge and use it". Another commented that having a physical representation helped support their lecture material, such that "being told in lectures that many cycles of charge and discharge can result in a breakdown of structure is difficult to visualise. However, moving the lithium blocks in and out of the structure repeatedly resulting in loss of alignment gives a really nice visual aid that I can use in my revision."

Finally, with the multiple scenarios the tower block sets can show, one student "was surprised how many concepts the set could introduce and it's interesting to see how it could be used as an interactive demonstration taking up an entire exercise in class, or as the starting point for much more complex chemistry in later years, leading into discussion of how removal of lithium is accompanied by a change in cobalt oxidation state and what this means for the battery setup."

A suggested improvement to this demonstration was to show the external circuit with the movement of electrons; to show this, a pipe cleaner attached to the current collector topped with moveable beads to represent the electrons was suggested.

The tactile set has been reviewed by two teachers who specialize in the education of visually impaired students. The feedback we have received was extremely positive, where the set was praised for its use of textures and contrasting colors and for the highly interactive nature of the set, such as when the tower block set is collapsed when fast charging is performed. From this feedback and to ensure suitability, these are the suggested improvements related to a modification of the reversible set which was used to show the effect of different charge rates: In this set, the blocks were constructed so that the graphite electrode was on one side and the oxide electrode on the other side, as mentioned previously (Figure 5). The feedback suggested that having both electrodes on the same tower (one at front, the other at the back) may confuse students, who rely heavily on exploring the textures. Thus, the recommendation was to have each tower represent a single electrode, with no decoration on the reverse. With this amendment, the only activity which will be impacted with this modification will be the rate-charging demonstration, where two students are required. Instead of running the activity simultaneously, one student should operate as a slow charge such that the structure remains intact, and after resetting, a second student uses the same tower block set operating at fast charge. The second recommendation, following this alteration, would be for the educator to play a sounding beep to set the contrasting paces of lithium-ion removal from the tower sets. This will help support the students in timing the block removal and prevent any confusion in what they should be aiming for. This addition would benefit sighted students also.

We acknowledge that feedback that comes directly from blind and visually impaired students will be most beneficial, and we plan to conduct this survey at a later date and make suitable adjustments based on students' feedback to ensure the activity is the most beneficial it could possibly be for them.

CONCLUSIONS

To summarize and conclude, we have illustrated a standard tower block set to be akin to the two electrodes that are found in a Li-ion battery. The battery tower block sets allow us to show the intercalation chemistry of the lithium ions, through the removal of the blocks from the oxide electrode to the graphite electrode upon charging, with the reverse process occurring on discharging. A range of other battery chemistry effects can be considered through comparing the rate of charge, with an activity involving two students who remove the blocks at different rates. The lack of ability to remove three lithium-ion blocks from one layer also helps reinforce structural aspects of the $LiCoO_2$ material, whereby not all of the lithium can be removed. Finally, when removing and reinserting blocks into the tower sets, the longitudinal blocks of the purple/red cobalt oxide layers or the gray graphite layers are gradually knocked off center. This effect can help to explain the degradation effects Li-ion batteries can experience from repeated cycling. A survey was undertaken, and $n = 81$ responses were collected. The responses consisted of university students, a specialist adult group, and secondary school children for pre- and post-demonstration. Overall, the battery tower block game received positive feedback for its use in reinforcing battery education. Furthermore, we believe that additional activities can also be developed using this resource, including multiple sets to help to explain how the battery management system of a full EV (electric vehicle) pack operates, and this is the subject of our future development in this area.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00282.

List of items and instructions to reproduce the battery tower block game sets, with the associated components of the battery of the correct dimensions, which can be printed directly onto the recommended sticker paper and affixed to the tower blocks, and additional results from the surveys (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

Demonstration videos with both sets are available at the listed sites: painted (video A, https://www.youtube.com/watch?v=g6_ETgt2ME0) and tactile (video B, https://www.youtube.com/watch?v=PoeM-7E1pDA), with an additional voice over (video C, https://www.youtube.com/watch?v=DcgWkGxoh48) which provides further points for the educators.

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