Physical Electrochemistry in the Undergraduate Curriculum: A Critical Assessment

by Ann Abraham, Nikola Matic, Denis Martins de Godoi, Jing Xu, Zhange Feng, Imre Treufeld, Doe Kunsa, Adriel Jebaraj, and Daniel Scherson

Focusing on the Issues

Over the last decade, electrochemistry has permeated the lives of vast segments of the human population by providing power sources for portable communication, including phones, computers, and ever more complex multifunctional devices. This trend will continue in the foreseeable future owing to the impending introduction of large fleets of hybrid and fully electrical cars.

The reasons behind this technological transition are two-fold. First, the depletion of oil reserves worldwide will lead to an increase in the price of gasoline and other fossil-derived fuels and thus affect the cost of transportation of goods in general. This factor is being exacerbated by the rapid economic growth of highly populated countries, such as China and India, which will increase market demand. The second, and perhaps more alarming factor, relates to the increase in the amount of carbon dioxide in the atmosphere, a phenomenon believed to be responsible for the rise in the average earth temperature. Failure to contain this growing threat may lead to environmental changes the severity of which continues to be the subject of much heated debate.

This uncertain outlook has stimulated renewed interest in the further development and implementation of efficient and economical energy conversion and energy storage schemes aimed at utilizing in an effective fashion, intermittent sources, such as solar and wind, as well as improving the management of the electrical grid and thus mitigate losses. Although physical approaches such as pumping water uphill or compressing gases currently represent the cheapest means of storing energy per cycle, their applicability is restricted by geological and geographical factors. Far more versatile, but also more expensive, are electrochemically-based devices including batteries, electrolyzers, electrochemical capacitors, and fuel cells.

Meeting the energy and environmental challenges will demand the training of new generations of scientists and engineers in non-traditional, areas. In our view, the first step in the process is to raise awareness of students at the high school and undergraduate levels—not only of the problems we now face as a society, but also about the crucial role they could play in solving them—aimed at whetting their intellectual appetite. Whereas electrochemistry has gained strong academic, well-deserved representation in the area of analytical chemistry, its presence in physical chemistry, a discipline critical to tackling the complexities of electrochemical energy storage and energy conversion devices, and other key technologies such as corrosion prevention, appears to have stagnated for some time.

This brief article examines the scope and critically assesses material covered by more than a dozen of the most popular textbooks in physical chemistry for undergraduate students in the specific areas of electrochemistry and physical electrochemistry. In addition, it discusses some of difficulties encountered by instructors attempting to introduce key aspects of these fields in their curricula, as well as making a series of recommendations regarding content authors should consider incorporating in future editions of their textbooks.

Current Outlook

We have analyzed the content of about a dozen physical chemistry textbooks regarded as among the most commonly used by undergraduate educators in the U.S. to identify the extent and quality of the material therein covered in the specific area of physical electrochemistry. The results of this analysis are summarized in Table I and indicate that thermodynamics was by far the most widely and thoroughly represented including excellent expositions of such topics as Debye Hückel theory, standard redox potentials, and electrochemical cells.

In stark contrast, and with only a few notable exceptions, the area of heterogeneous electron transfer reactions at electrode–electrolyte interfaces received hardly any attention. Most of the textbooks that did address some of these issues failed in our view to provide clear explanations of key aspects of these processes, such as those upon which Marcus theory is based and the effect of the applied potential on the kinetics of redox reactions. Also no mention was made of the Butler-Volmer equation and the meaning of transfer coefficients, which are key to electrochemical kinetics in general. The examples provided as illustrations of batteries included the classical, albeit seldom heard of Weston and Daniell's cells. In fact, it was amusing to find a subsection in one of the textbooks archaically titled "voltaic piles."

Most importantly, however, none of the books consulted would have ignited in the authors an interest in pursuing a career in electrochemistry. We suspect this attitude would not be unlike that of instructors who themselves may not be acquainted with the exciting aspects of electrochemistry and would not be compelled to do so by reading the vast majority of these textbooks. Some may argue that the mathematics of electrochemistry is too complex to teach to chemists; however, the effort required would not exceed that associated with other fields, such as quantum mechanics or statistical thermodynamics, which are obligatory in the curriculum of most institutions granting a BS or BA in chemistry.

Targets of Opportunity

Authors of these textbooks should take advantage of material treated in its most fundamental forms, and find means to extend it to modern technological applications. Examples would include extensions of the Debye Huckel theory of electrolytes to interfacial charging of ideal polarizable electrodes, a concept that relates directly to the operation of electrochemical double

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Table I. Electrochemistry Coverage in Physical Chemistry Textbooks.

	Textbook										
Topics	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Physical Fundamentals											
Electrical quantities and units		◆		◆	◆	◆		◆	◆	◆	◆
Electrical field		◆		◆	◆	◆		◆	◆	◆	◆
Electrostatic potentials		◆	◆	◆	◆	◆		◆	◆	◆	◆
Faraday’s law	◆					◆		◆	◆		◆
Physics of Interfaces											
Double layer models											◆
Electrical double layer: Debye-Huckel theory		◆	◆	◆		◆		◆	◆	◆	◆
Electrical double layer: Gouy-Chapman and Stern model			◆		◆	◆					◆
Surface charges and capacitances					◆	◆					
Electrochemical Thermodynamics											
Thermodynamics of ions	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Nernst equation	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Potentials			◆	◆	◆	◆					◆
Chemical potential	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Electrochemical potential	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆
Standard electrode potential	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Equilibrium constants	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
EMF	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆
Activities	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Conduction of Electricity											
Conductivity		◆		◆	◆	◆		◆	◆		◆
Molar conductance		◆		◆	◆			◆	◆		◆
Ionic transport (transport number, mobility, Hittorf method)		◆	◆	◆	◆			◆	◆		◆
Bridges and measurement		◆	◆	◆	◆	◆					◆

layer capacitors as energy storage devices found in container port cranes around the globe. Also long overdue is the use of lithium ion batteries as examples that should replace the Weston or Daniell’s voltaic piles, as well as the broad introduction of proton exchange membrane electrolyte based fuel cells instead of their historical liquid based predecessors. There is no question that concepts such as activity coefficients and Hittorf cells are key to understanding fundamental physical chemistry, but without establishing strong links to the familiar world around us and a pinch of pizzazz, such concepts will be learned and soon forgotten.

Yet another challenging aspect of the teaching of most science disciplines relates to the ever shorter time instructors have at their disposal to satisfy curricular requirements. As the adage goes, there is “Too much to teach, too little time in the classroom.” Should a few lectures remain after covering the essentials, instructors naturally gravitate toward specialized topics they may have encountered in their own education or in their research activities to wrap up the term. It is difficult to expect instructors to spend their time studying material alien to them to teach that material with the passion an expert would. It can be envisioned within the high technology environment we live in that a means to bridge this gap is by exposing students to professionally-edited material where instructors become moderators rather than protagonists. In fact, there are already hundreds if not thousands of such lectures available on the Web. Unfortunately, and somewhat surprising, such material is glaringly lacking in the area of physical electrochemistry. It is here that professional societies such as ECS can make an impact by sponsoring, promoting, and supporting development of educational material drawing from the extraordinary collective expertise of its members.

It is hoped that this brief evaluation of physical electrochemistry in undergraduate education will serve to draw attention within our Society for concrete action toward fulfilling a most rewarding and worthy goal—attracting the best young minds to meet one of the difficult challenges we now face as a society. ■

About the Authors

Ann Abraham earned her BA in chemistry (ACS certified) from Hiram College (U.S.) in 1988. She earned a PhD in organic chemistry from the University of Pittsburgh in 1993 in the area of organic radical methodology. She spent eight years synthesizing and purifying organic targets of interest including C-14 radio-labeled materials in industry at Ricerca, LLC. She taught at Notre Dame College in South Euclid, Ohio for two years and is presently at Kent State University-Ashtabula where she is a tenured, Associate Professor in Chemistry. Her current research interests focus on the modification of nanoclays, electron beam irradiation of polymer blends, and kid chemistry outreach. She is presently the NE Ohio Coordinator of National Chemistry Week. She may be reached at aabraha3@kent.edu.

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	Textbook										
Topics	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Electrodes											
Reference	◆	◆	◆	◆	◆	◆		◆	◆		◆
Working				◆		◆		◆			◆
Cells											
Galvanic	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆
Electrolysis	◆	◆			◆	◆		◆	◆		◆
Working galvanic cell	◆	◆				◆	◆	◆			◆
Electrochemical Kinetics											
Overpotential						◆					◆
Butler Volmer equation						◆					◆
Tafel equation/plot						◆					◆
Voltammetry											◆
Linear sweep voltammetry											◆
Cyclic voltammetry											◆
Differential pulse voltammetry											◆
Corrosion					◆						◆
Applications											
Conductometry				◆				◆	◆		
pH measurements	◆			◆	◆			◆	◆	◆	◆
Fuel cells	◆		◆		◆			◆		◆	◆
Potentiometric titration	◆			◆	◆			◆	◆		
Batteries	◆	◆	◆		◆			◆			◆

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catalyst/support interfaces to application of surface science to modern electrochemical problems. In his current project he studies the relationship between small molecules adsorption on different crystalline facets in UHV with their equivalents in the electrochemical nitrogen cycle. He may be reached at nikola.matic@case.edu.

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