

## Electrochemical Impedance Spectroscopy

ECH 6851 Section TR6Y 28692

**Class Periods:** Tuesday, Periods 6-7, 12:50 PM – 2:45 PM, MAEB 0238

Thursday, Periods 6, 12:50 PM - 1:40 PM, MAEB 0238

**Academic Term:** Spring 2024

### **Instructor:**

Mark E. Orazem

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352-392-6207

Office Hours: Friday, 1:00-3:00 PM ChE 327

### **Peer Mentor:**

Please contact through the Canvas website

- Yunhan Chuai, [yunhanchuai@ufl.edu](mailto:yunhanchuai@ufl.edu), Office Hours: Monday, 3:00-5:00 PM ChE 325

### **Course Description**

3 credit hours. Intended for chemists, physicists, materials scientists, and engineers with an interest in applying electrochemical impedance techniques to study a broad variety of electrochemical processes.

### **Course Pre-Requisites / Co-Requisites**

Prerequisites: familiarity with applications of differential equations.

### **Course Objectives**

Impedance spectroscopy represents the confluence of a significant number of disciplines, and successful training in the use and interpretation of impedance requires a coherent education in the application of each of these disciplines to the subject. In addition to learning about impedance spectroscopy, the student will gain a better understanding of the general philosophy of scientific inquiry.

The topics include:

- Fundamentals of complex variables, electrical circuits, and electrochemistry needed to understand electrochemical impedance spectroscopy.
- Methods used to measure impedance and other transfer functions, including an understanding of frequency-domain techniques and the approaches used by impedance instrumentation. This understanding provides a basis for evaluating and improving experimental design.
- Methods for developing deterministic models of impedance response from physical and kinetic descriptions.
- Methods for interpretation of impedance data, ranging from graphical methods to complex nonlinear regression.
- Conceptual understanding of stochastic, bias, and fitting errors in frequency-domain measurements, including the Kramers-Kronig relations and their application to spectroscopy measurements.
- Philosophy for electrochemical impedance spectroscopy that integrates experimental observation, model development, and error analysis.

The coursework will include homework problems, exams, and a group project in which the concepts learned in the class will be applied to a specific set of impedance data. Students will use a free computer program developed in Prof. Orazem's group to identify the error structure of impedance data and to regress user-defined models to the data. The textbook for the course was co-authored by Prof. Orazem.

### **Materials and Supply Fees**

None.

### **Required Textbooks and Software**

M. E. Orazem and B. Tribollet, *Electrochemical Impedance Spectroscopy*, 2nd edition, John Wiley & Sons, Hoboken, New Jersey, 2017, ISBN: 9781118527399.

Note: Exams will be open-book, and use of computers and phones will be prohibited. Thus, a paper copy of the book will be required. The first edition is not an acceptable substitute.

W. Watson and M. E. Orazem, *EIS: Measurement Model Program, Version 1.8, ECSArXiv*, 2023, <https://doi.org/10.1149/osf.io/g2fjm>. This download is a Windows installation file, and the program is free for use. Mac users will need to use a Windows emulator.

### **Recommended Materials**

Other materials will be made available on the course website.

### **Course Schedule**

The tentative schedule for exams and materials covered is attached.

### **Attendance Policy, Class Expectations, and Make-Up Policy**

Attendance is required. Attendance records will be used to guide the determination of final grades. Cell phones and other distractions may not be used in class. Excused absences must be consistent with university policies in the Graduate Catalog (<https://catalog.ufl.edu/graduate/regulations>) and require appropriate documentation. Additional information can be found here: <https://gradcatalog.ufl.edu/graduate/regulations/>.

### **Evaluation of Grades**

The nature of this material is that mastery can be obtained only through diligent solution of homework problems. Discussion with classmates is encouraged, but the final solution to homework problems should represent your own efforts.

The grading schedule used will depend on the size of the class. If the class is large, the grades will be based solely on exams. If the class size is moderate, homework and a group project may also be included in the calculation of the final grade. The tentative grading is:

Homework	10%
Mid-term exams (2)	50%
Final exam or Group Project	40%

The group project will involve application of regression analysis to impedance data. The manuscript should be of a quality sufficient for submission to relevant journals, and I anticipate that manuscripts will be submitted.

### **Grading Policy**

Grades for this class are curved at the discretion of the instructor. Attendance and class participation will be considered.

### **Relevant Aspects of the Chemical Engineering Policy on Exams**

- a) All exams will include the honor pledge and students must sign their name by the pledge.
- b) All students must leave backpacks, bags, etc., in the front of the classroom as they enter.
- c) Students are asked not to bring cell phones in the exam. In case they do, they have to place the cell phones in the front of the classroom. The department and proctors have no responsibility in case of theft (cell phones should not be brought). A cell phone discovered on a student's person may result in a zero grade for the exam. If a student is expecting an important call, he or she must discuss this with the proctors before starting the exam.
- d) Students are required to remove their hats during the exam and place them in the front of the classroom.
- e) In open book exams no printed material other than the textbook is allowed. A solution manual or printouts from solution manuals will result in a zero grade for the exam and additional harsher penalties.
- f) Any talking between students is strictly prohibited and will result in a zero grade for the exam.
- g) Students may not leave the room before turning in the exam.

More information on UF grading policy may be found at:

[UF Graduate Catalog](#)  
[Grades and Grading Policies](#)

### ***Students Requiring Accommodations***

Students with disabilities who experience learning barriers and would like to request academic accommodations should connect with the disability Resource Center by visiting <https://disability.ufl.edu/students/get-started/>. It is important for students to share their accommodation letter with their instructor and discuss their access needs, as early as possible in the semester.

### ***Course Evaluation***

Students are expected to provide professional and respectful feedback on the quality of instruction in this course by completing course evaluations online via GatorEvals. Guidance on how to give feedback in a professional and respectful manner is available at <https://gatorevals.aa.ufl.edu/students/>. Students will be notified when the evaluation period opens, and can complete evaluations through the email they receive from GatorEvals, in their Canvas course menu under GatorEvals, or via <https://ufl.bluera.com/ufl/>. Summaries of course evaluation results are available to students at <https://gatorevals.aa.ufl.edu/public-results/>.

### ***In-Class Recording***

Students are allowed to record video or audio of class lectures. However, the purposes for which these recordings may be used are strictly controlled. The only allowable purposes are (1) for personal educational use, (2) in connection with a complaint to the university, or (3) as evidence in, or in preparation for, a criminal or civil proceeding. All other purposes are prohibited. Specifically, students may not publish recorded lectures without the written consent of the instructor.

A “class lecture” is an educational presentation intended to inform or teach enrolled students about a particular subject, including any instructor-led discussions that form part of the presentation, and delivered by any instructor hired or appointed by the University, or by a guest instructor, as part of a University of Florida course. A class lecture does not include lab sessions, student presentations, clinical presentations such as patient history, academic exercises involving solely student participation, assessments (quizzes, tests, exams), field trips, private conversations between students in the class or between a student and the faculty or lecturer during a class session.

Publication without permission of the instructor is prohibited. To “publish” means to share, transmit, circulate, distribute, or provide access to a recording, regardless of format or medium, to another person (or persons), including but not limited to another student within the same class section. Additionally, a recording, or transcript of a recording, is considered published if it is posted on or uploaded to, in whole or in part, any media platform, including but not limited to social media, book, magazine, newspaper, leaflet, or third party note/tutoring services. A student who publishes a recording without written consent may be subject to a civil cause of action instituted by a person injured by the publication and/or discipline under UF Regulation 4.040 Student Honor Code and Student Conduct Code.

### ***University Honesty Policy***

UF students are bound by The Honor Pledge which states, "We, the members of the University of Florida community, pledge to hold ourselves and our peers to the highest standards of honor and integrity by abiding by the Honor Code. On all work submitted for credit by students at the University of Florida, the following pledge is either required or implied: "On my honor, I have neither given nor received unauthorized aid in doing this assignment." The Honor Code (<https://sccr.dso.ufl.edu/process/student-conduct-code/>) specifies a number of behaviors that are in violation of this code and the possible sanctions. Furthermore, you are obligated to report any condition that facilitates academic misconduct to appropriate personnel. If you have any questions or concerns, please consult with the instructor or TAs in this class.

## **Commitment to a Safe and Inclusive Learning Environment**

The Herbert Wertheim College of Engineering values varied perspectives and lived experiences within our community and is committed to supporting the University's core values, including the elimination of discrimination. It is expected that every person in this class will treat one another with dignity and respect regardless of race, creed, color, religion, age, disability, sex, sexual orientation, gender identity and expression, marital status, national origin, political opinions or affiliations, genetic information, and veteran status.

If you feel like your performance in class is being impacted by discrimination or harassment of any kind, please contact your instructor or any of the following:

Your academic advisor or Graduate Program Coordinator

HWCOE Human Resources, 352-392-0904, [student-support-hr@eng.ufl.edu](mailto:student-support-hr@eng.ufl.edu)

Curtis Taylor, Associate Dean of Student Affairs, 352-392-2177, [taylor@eng.ufl.edu](mailto:taylor@eng.ufl.edu)

Toshikazu Nishida, Associate Dean of Academic Affairs, 352-392-0943, [nishida@eng.ufl.edu](mailto:nishida@eng.ufl.edu)

## **Software Use**

All faculty, staff, and students of the University are required and expected to obey the laws and legal agreements governing software use. Failure to do so can lead to monetary damages and/or criminal penalties for the individual violator. Because such violations are also against University policies and rules, disciplinary action will be taken as appropriate. We, the members of the University of Florida community, pledge to uphold ourselves and our peers to the highest standards of honesty and integrity.

## **Student Privacy**

There are federal laws protecting your privacy with regards to grades earned in courses and on individual assignments. For more information, please see: <https://registrar.ufl.edu/ferpa.html>

## **Campus Resources:**

### Health and Wellness

#### **U Matter, We Care:**

Your well-being is important to the University of Florida. The U Matter, We Care initiative is committed to creating a culture of care on our campus by encouraging members of our community to look out for one another and to reach out for help if a member of our community is in need. If you or a friend is in distress, please contact [umatter@ufl.edu](mailto:umatter@ufl.edu) so that the U Matter, We Care Team can reach out to the student in distress. A nighttime and weekend crisis counselor is available by phone at 352-392-1575. The U Matter, We Care Team can help connect students to the many other helping resources available including, but not limited to, Victim Advocates, Housing staff, and the Counseling and Wellness Center. Please remember that asking for help is a sign of strength. In case of emergency, call 9-1-1.

**Counseling and Wellness Center:** <https://counseling.ufl.edu>, and 392-1575; and the University Police Department: 392-1111 or 9-1-1 for emergencies.

#### **Sexual Discrimination, Harassment, Assault, or Violence**

If you or a friend has been subjected to sexual discrimination, sexual harassment, sexual assault, or violence contact the **Office of Title IX Compliance**, located at Yon Hall Room 427, 1908 Stadium Road, (352) 273-1094, [title-ix@ufl.edu](mailto:title-ix@ufl.edu)

#### **Sexual Assault Recovery Services (SARS)**

Student Health Care Center, 392-1161.

**University Police Department** at 392-1111 (or 9-1-1 for emergencies), or <http://www.police.ufl.edu/>.

Academic Resources

**E-learning technical support**, 352-392-4357 (select option 2) or e-mail to Learning-support@ufl.edu.  
<https://lss.at.ufl.edu/help.shtml>.

**Career Connections Center**, Reitz Union, 392-1601. Career assistance and counseling; <https://career.ufl.edu>.

**Library Support**, <http://cms.uflib.ufl.edu/ask>. Various ways to receive assistance with respect to using the libraries or finding resources.

**Teaching Center**, Broward Hall, 392-2010 or 392-6420. General study skills and tutoring.  
<https://teachingcenter.ufl.edu/>.

**Writing Studio, 302 Tigert Hall**, 846-1138. Help brainstorming, formatting, and writing papers.  
<https://writing.ufl.edu/writing-studio/>.

**Student Complaints Campus**: <https://sccr.dso.ufl.edu/policies/student-honor-code-student-conduct-code/>; <https://care.dso.ufl.edu>.

**On-Line Students Complaints**: <https://distance.ufl.edu/getting-help/>; <https://distance.ufl.edu/state-authorization-status/#student-complaint>.

## Tentative Schedule

Date	Topics Covered
Part I. Background	
Jan. 9	Chapter 1. Complex Variables. Yunhan Chuai guest lecturer
Jan. 11	
Jan. 16	Introduction to Impedance Spectroscopy / History of Impedance Spectroscopy (Front matter)
Jan. 18	Electrical Circuits (Chapter 4)
Part II. Experimental Considerations	
Jan. 23	Experimental Methods (Chapters 7 and 8)
Jan. 25	
Part III. Process Models	
Jan. 30	Equivalent Circuit Analogs (Chapter 9)
Feb. 1	
Feb. 6	Kinetic Models (Chapter 10)
Feb. 8	
Feb. 13	Diffusion Impedance (Chapter 11)
Feb. 15	
Feb. 20	Exam 1
Feb. 22	Impedance of Materials (Chapter 12)
Feb. 27	Time-Constant Dispersion (Chapter 13)
Feb. 29	
Mar. 5	Constant-Phase Elements (Chapter 14)
Mar. 7	

Mar. 12	Spring Break
Mar, 14	
Part IV. Interpretation Strategies	
Mar. 19	Graphical Methods (Chapters 17 and 18)
Mar. 21	
Mar. 26	Exam 2
Mar. 28	Complex Nonlinear Regression (Chapter 19)
Part V. Statistical Analysis	
Apr. 2	Error Structure of Impedance Measurements (Chapter 21)
Apr. 4	
Apr. 9	The Kramers–Kronig Relations (chapter 22)
Apr. 11	
Putting It All Together	
Apr. 16	The Measurement Model
Apr. 18	
Apr. 23	