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BOARD # 267: Making Nuclear Magnetic Resonance Resonate with Students: An NSF-IUSE Project that Aims to Integrate NMR into the Undergraduate Curriculum

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Motivation

Quantum science and engineering will play a huge role in the 21st-century STEM workforce, as evidenced by national investments in quantum industries [1] - [2] and the many interdisciplinary quantum information science and engineering (QISE) programs that have emerged in recent years. Science and engineering educators will play an important role in researching the best ways to prepare a thriving and diverse quantum workforce [3]. Nuclear magnetic resonance (NMR) is one quantum technology that historically has had a multidisciplinary impact - having garnered five Nobel prizes across physics, chemistry, and medicine - and still serves as a crucial analytic and diagnostic tool in applied science and engineering industries. NMR uses the quantum mechanical properties of atomic nuclei in an external magnetic field to provide information about a sample's chemical composition and structure. Magnetic resonance is used more broadly for manipulating quantum spins to encode information that is useful for magnetic resonance imaging (MRI) or quantum computation using solid-state qubits. Despite its underpinnings in fundamental physics, NMR currently has the biggest impact on the chemistry curriculum. The vital importance of NMR is highlighted in the current American Chemical Society (ACS) guidelines for undergraduate chemistry programs which states that "A functioning NMR (or reliable access to a functioning NMR that students use)" is a critical requirement for approved programs [4]. With the increasing availability of affordable benchtop NMR spectrometers, NMR can be much better utilized to teach valuable laboratory and research skills broadly across the undergraduate curriculum by being incorporated into more courses in chemistry, physics, medicine, and engineering. Integrating NMR into the undergraduate science and engineering curriculum would help build the STEM workforce of the future, where a basic understanding of quantum physics will become a necessity in emerging 21st-century technologies.

Project and objectives

Supported by an NSF-IUSE grant (DUE-2120545), we established an interdisciplinary and cross-institutional team to develop, assess, and disseminate modular lab-based materials that help integrate NMR across the undergraduate science and engineering curriculum. Along with our team's expertise in research-based science educational pedagogies such as investigative science learning environment (ISLE) [5], process-oriented guided inquiry learning [6], and peer-led team learning [7] - our materials also draw from the recent education research findings of the course-based undergraduate research experience [8] model. Over the past three years, these materials have been developed and tested at both Sarah Lawrence College (small, private, liberal arts college) and The City College of New York (large, public, research university) and reviewed by an advisory board of NMR and science education specialists across multiple scientific disciplines and institutions.

As part of our project objectives, we developed our materials to:

(1) make use of current pedagogical best practices for an engaged and inclusive science learning environment,
(2) provide students with class-based undergraduate laboratory experiences that introduce research skills and emulate experimental research in a lab, and
(3) be easily adapted and adopted for use in a wide array of educational environments and courses in the science and engineering curriculum.

Developed materials

The developed materials consist of laboratory modules (Physics Modules 1 - 12 and Chemistry Modules A - E) that fit into roughly 1.5-hour class periods with additional extension activities and/or experiments that can be performed on benchtop NMR spectrometers. These materials introduce the topics without any expectation of prior college-level science or math courses and have been successfully used as part of standard introductory science courses where they can make the most impact - including general chemistry, general physics, and first-year seminars. We also designed the materials to be accessible without direct access to NMR equipment by providing videos of demonstrations using equipment and results from NMR experiments that students can analyze. The modules are available online as an e-text or downloadable as editable documents for faculty to incorporate into their course materials. Along with the laboratory modules, we include instructor's manuals and supplemental materials (such as slides, assessments, extension activities, and example experiments) freely available on our website [9].

In agreement with pedagogical best practices, an exemplar module contains:

- **Expected Learning Outcomes**
- **Example Real-World Application** that features technologies that make use of the topics covered in the module
- **Highlighted Scientists** from different scientific fields and backgrounds to help students see parts of their interests and experiences reflected in the materials
- **Classroom Discussion Prompts** to recall prior knowledge and experiences that can serve as a foundation for the new topic
- **Guided Inquiry Activities** that intersperses information, hands-on activities, and questions to guide students to discover basic physical principles and develop physical models
- **Opportunities for Students to Design and Perform Experiments** to test models and analyze NMR data
- **Application and Reflection Questions** so students can apply their knowledge in new

ways and reflect on what they have learned

Our modular design anticipates faculty picking and choosing the individual modules that can easily snap into their current curriculum and courses, depending on the focus of the material they want to cover. The course implementation examples below demonstrate how modules can be integrated throughout the standard undergraduate science curriculum or used as science outreach for high schoolers or early college programs.

Standard Chemistry Courses	**Lab Unit**	**Class 1** Module Topic	**Class 2** Module Topic	**Class 3** Module Topic	**Class 4** Module Topic
General Chemistry	Intro to H-1 and C-13 NMR Spectroscopy	H-1 NMR	C-13 NMR		
Organic Chemistry	Using NMR to Study Organic Molecules	Coupling Constants & Exchange	(DEPT)		
Analytical Chemistry	Using Multi-Pulse Sequences and 2D NMR	(DEPT)	COSY		

Standard Physics Courses	**Lab Unit**	**Class 1** Module Topic	**Class 2** Module Topic	**Class 3** Module Topic	**Class 4** Module Topic
General Physics - Mechanics	Quantum spin and spin dynamics.	*Why MR?*	*Spin Intro*	Larmor Precession	
General Physics - E&M	Spin control and basic physics behind NMR spectroscopy	*Larmor Precession*	Spin Control via Pulses	NMR Spectrometer Basics	
Intermediate - Oscillations and Waves	Free Induction Decay, Fourier Transform and FFT, NMR bridge to QM	*NMR Spectrometer Basics*	FFT Intro	FFT Extension	(QM Intro)
Advanced Physics Lab	Relaxation and MR Applications	Relaxation	Spin Echoes	(Solid-State NMR)	(MRI)

Outreach Program	**Focus**	**Class 1**	**Class 2**	**Class 3**	**Class 4**
NMR Spectroscopy Basics	Running 1D NMR Experiments and Analyzing Spectra	*NMR Spectrometer Basics*	H-1 NMR	(C-13 NMR)	Coupling Constants & Exchange
Magnetic Resonance Applications for Medicine	MR applications to spectroscopy and imaging	*Why MR?*	NMR Spectrometer Basics	MRI	
NMR Bridge to Quantum Mechanics (QM)	Quantum postulates with NMR examples	Spin Control via Pulses	Relaxation	*Spin Echoes*	QM Intro
NMR Bridge to Quantum Computing (QC)	Quantum computing basics with NMR examples	Spin Control via Pulses	*Spin Echoes*	(QM Intro)	QC Intro

Key
Italic - Can be done as an interactive, pre-reading assignment
(Parenthetical) - Optional module to consider including depending on course focus, student background and interest, and time constraints.

Evaluation methodology

In consultation with our external evaluator, Dedra Demaree, we have evaluated our project objectives through the collection and analysis of both quantitative and qualitative data collected over multiple implementations of the modules at Sarah Lawrence College and The City College of New York. Project evaluation included well-established surveys of science identity (STEM-PIO-1 [10]), expert-like mindset (E-CLASS [11], URSSA [12], SALG [13]), student perceptions of doing authentic research (Q-Sort [14]), focus group interviews with students and instructors, and analysis of video recordings of different classroom implementations of the modules.

Evaluation result summary

The STEM-PIO-1 results showed positive gains in the science identity of students pre/post module implementation and statistically significant gains with the undergraduate student researchers who participated in the project. We also measured statistically significant increases in the expert-like mindset of the students toward experimental physics (E-CLASS), self-assessed research skills (URSSA), and self-assessed learning gains (SALG). The focus group interviews with students and Q-Sort helped improve the materials over the two years of implementation as we better aligned the students' perception of doing authentic research with the instructor's intentions. Based on an ISLE study [15], we coded student engagement in the video recordings of the materials used in the class implementations. We found that students spent most of their class time "sense-making", much more than in traditional laboratory courses and even exemplar ISLE labs. We aim to publish the details of our evaluation results and analysis in educational journals in the upcoming years.

Conclusions

Our research shows that students using our modules not only successfully master the NMR content, they also: (1) spend over four times as much time sense-making using our modules as in a traditional lecture course, (2) demonstrate positive scientific identity shifts, and (3) make statistically significant gains in learning attitudes about science and self-assessed research skills. An additional benefit we observed was that both instructors and students enjoyed using the modules and instructors noticed their students' increased confidence in their understanding of the material and interest in pursuing a career in STEM fields. We see the integration of these modules into the undergraduate science and engineering curriculum as a positive step towards the larger goal of expanding the pool of quantum- and research-literate workers needed for the 21st-century STEM workforce.

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References

[1] National Quantum Initiative, https://www.quantum.gov/. [Accessed Jan. 11, 2025].

[2] NSF Focus Area: Quantum Information Science, https://new.nsf.gov/focus-areas/quantum. [Accessed Jan. 11, 2025].

[3] I. Siddiqi, D. Gil, and J. S. Broz, “Quantum for All,” *Physics*, vol. 13, pp. 143, Sept. 2020.

[4] 2023 ACS Guidelines for Undergraduate Chemistry Programs, https://www.acs.org/content/dam/acsorg/about/governance/committees/training/acsapproved/degreeprogram/1-guidelines-approved-jan2023-2.pdf. [Accessed Jan. 6, 2025].

[5] E. Etkina and A. Van Heuvelen, "Investigative Science Learning Environment - A Science Process Approach to Learning Physics," *Research-Based Reform of University Physics*, Reviews in PER Vol. 1, E. F. Redish and P. J. Cooney, Eds. College Park, MD: AAPT, 2007.

[6] “What is POGIL?”, https://pogil.org/what-is-pogil. [Accessed Jan. 11, 2025].

[7] D. K. Gosser, M. S. Cracolice, J. A. Kampmeier, V. Roth, V. S. Strozak, and P. Varma-Nelson, *Peer-led Team Learning: A Guidebook.* Upper Saddle River, NJ: Prentice Hall, 2001.

[8] E. Dolan, *Course-Based Undergraduate Research Experiences: Current Knowledge and Future Directions*, Washington, D.C: National Academies of Sciences, Engineering, and Medicine, 2016. [Online]. Available: https://sites.nationalacademies.org/cs/groups/dbassesite/documents/webpage/dbasse_177288.pdf. [Accessed Jan. 11, 2025].

[9] Integrating Nuclear Magnetic Resonance Into the Undergraduate Science Curriculum, https://sites.google.com/view/makingnmr/home. [Accessed Jan. 7, 2025].

[10] M. McDonald, V. Zeigler-Hill, J. Vrabel, and M. Escobar, “A Single-Item Measure for Assessing STEM Identity,” *Frontiers in Education*, vol. 4, no. 78, Jul. 2019. [Online]. Available: https://doi.org/10.3389/feduc.2019.00078. [Accessed Jan. 7, 2025].

[11] B. Wilcox and H. Lewandowski, “Students’ views about the nature of experimental physics,” *Physical Review - Physics Education Research*, vol. 13, p. 020110, Aug. 2017.

[12] Evaluation Tools: Undergraduate Research Student Self-Assessment (URSSA), https://www.colorado.edu/eer/research-areas/undergraduate-research/evaluation-tools-undergraduate-research-student-self. [Accessed Jan. 7, 2025].

[13] E. Seymour, D. Wiese, A.-B. Hunter, and S. Daffinrud, “Student Assessment of Learning Gains (SALG) CAT,” Jan. 1997. [Online]. Available: https://www.researchgate.net/publication/252112013_Student_Assessment_of_Learning_Gains_SALG_CAT. [Accessed Jan. 7, 2025].

[14] Y. Lin, D. Demaree, X. Zou, and G. Aubrecht, “Student Assessment Of Laboratory In Introductory Physics Courses: A Q-sort Approach,” *AIP Conference Proceedings*, vol. 818, pp. 101-104, Feb. 2006. Available at: https://aip.scitation.org/doi/abs/10.1063/1.2177033. [Accessed Jan. 7, 2025].

[15] A. Karelina and E. Etkina, “Acting like a physicist: Student approach study to experimental design,” *Physical Review Special Topics - Physics Education Research*, vol. 3, p. 020106, Oct. 2007.