Module 12 - What Can NMR Teach Us About Quantum Computing?
Instructor's Manual

Suggested Prior Modules

Modules 4, 7, 11

Particular prior knowledge from Module 4 that students are expected to have already learned:

- The Bloch sphere representation for two-level quantum systems
- Using the Bloch simulator, including spin initialization and applying pulses
- Nutation and pulses, particularly how longer pulses cause more rotation of the spins on the Bloch sphere

This is the most important prior module to have students do in preparation for Module 12. *If you do not have time to complete the entirety of Module 4 in class, then this module can be used as a longer, interactive assignment completed outside of class. It is estimated to take about 1.5 - 2 hours for students to complete asynchronously.*

Particular prior knowledge from Module 7 that students are expected to have already learned:

- Interpreting Bloch sphere dynamics from pulse sequences.

The Background Information and Observation Experiments: Spin Echoes sections should suffice as preparation for this module and could be done as part of a pre-reading assignment.

Particular prior knowledge from Module 11 that it is helpful (but not necessary) for students to have already seen:

- The State Vector Rule Postulate
- The Outcome Probability Postulate

If you do not have time to complete Module 11 in class, then these sections can be used as part of a pre-reading assignment.

Suggested Use:

The instructions below are suggestions to help students engage with the material in class. However, all sections and questions in this module can successfully be done asynchronously online to serve as an excellent entryway for introductory science students to be introduced to the fundamentals of quantum computing through NMR examples.

This material is based upon work supported by the National Science Foundation under award DUE-2120545. Making Nuclear Magnetic Resonance Resonate With Students: Integrating NMR Into the Undergraduate Science Curriculum,

Expected Learning Outcomes

At the end of this module, students should be able to...

1. *Provide key differences between classical and quantum computing*
2. *Use their understanding of spin dynamics on the Bloch sphere to find NMR analogues for single-qubit quantum gates*
3. *Interpret quantum circuit diagrams and accurately predict the probability of different outputs for given inputs*

Quantum Information Science and Technology

(20 minutes)

Suggested activity: Have students take turns reading aloud the text, along with the information in the margin. Have students do think-pair-share for the classwide discussion questions, and leave the classical versus quantum computing table up for reference if you are projecting the material. This section helps students discover for themselves possible motivations behind building quantum computers and start thinking about the potential challenges.

Qubits and the Bloch Sphere

(15 minutes)

Suggested activity: This section can be completed individually or in small groups where students are encouraged to read through the text, answer the questions, and check their answers with their group members before continuing.

Quantum Circuits and Single-Qubit Quantum Gates

(20 minutes)

Suggested activity: This section can also be completed individually or in small groups where students are encouraged to read through the text, answer the questions making use of this Bloch sphere simulator, and check their answers with their group members and/or the simulator before continuing. Making an equivalent pulse sequence for the Hadamard gate is a bit of a challenge, but there are different possible solutions (including using two pulses instead of one). As long as students find a sequence of pulses that puts the state into the correct ouput that matches the Hadamard operation, that is correct (even if it may not undergo exactly the same trajectory along the Bloch sphere as shown).

This material is based upon work supported by the National Science Foundation under award DUE-2120545. Making Nuclear Magnetic Resonance Resonate With Students: Integrating NMR Into the Undergraduate Science Curriculum,

Multiple Qubits

(30 minutes)

Suggested activity: The first subsection (Two-Qubit States and Entangled States) and its guided inquiry questions can be done in a similar style to the previous two sections. It may be helpful to then bring the class all together with the instructor to discuss the Entangled States and Spooky Action subsection to be sure students understand what makes entangled states special (namely, that measuring one of the qubits tells you information about the other qubit without needing to do any further measurements). This definition will help when students go thru the Two-Qubit Quantum Gates and Entangled States subsection and its guided inquiry questions (particularly questions 16 and 17, which are essentially the same situation, but students may need some helpful guidance from the instructor to determine if the output state will now be entangled. Having students think about how much you know about the target qubits' final state if you were to measure the control qubit's state should help students realize that the output of the quantum circuit shown is one of maximum entanglement. (Students might even be able to determine which Bell State it is likely to be!) Student who complete this section faster than others can go on to read the final Coupling and Entangling Spins subsection.

Making Quantum Computing a Reality

(15 minutes)

Suggested activity: This might be a good time to have the class come back together to see how they can apply their NMR knowledge to understand a simple NMR quantum computer. Have students take turns reading aloud the text, along with the information in the margin. Then students can do think-pair-share for the guided inquiry questions. (There may need to be some instructor guidance regarding the ability to send pulses at different Larmor frequencies in order to control a single nucleus without disturbing the state of another nucleus.)

Reflection Questions

(Any Remaining Time)

Suggested activity: In any remaining time you can choose some or all of the questions as a small group or individual reflection activity. The first three reflection questions are open-ended and provide the students with a chance to think critically and provide some justifications for their answers. The final question is ideal for use as a homework question, so students can practice recall as well as a reminder of the concepts they learned throughout the module. This is also a great introductory to the optional

This material is based upon work supported by the National Science Foundation under award DUE-2120545. Making Nuclear Magnetic Resonance Resonate With Students: Integrating NMR Into the Undergraduate Science Curriculum, CC 4.0 BY NC SA

extended activities you can have students do - [Quantum Enigmas Virtual Activities at IBM SKillsBuild.]()

All of these questions can all be completed outside of class as homework if class time is limited.

In the last 5 minutes of class: Give the students time at the end of class to assess themselves on the learning objectives using the provided rubric in the student worksheet copied below).

Follow this rubric to assess your work for this module:

Scientific Ability	Adequate	Needs improvement	Inadequate	Missing
Is able to provide key differences between classical and quantum computing	Can identify multiple key differences between classical and quantum computing.	Can identify some key differences between classical and quantum computing.	Some of the explanations contain errors or are incorrect.	No attempt is made to provide key differences.
Is able to use their understanding of spin dynamics on the Bloch sphere to find NMR analogues for single-qubit quantum gates	Correctly found NMR analogues for all single-qubit quantum gates.	Correctly found NMR analogues for nearly all of the single-qubit quantum gates.	More than one NMR analogue for the single-qubit quantum gates is incorrect.	No NMR analogues for single-qubit quantum gates is provided.
Is able to interpret quantum circuit diagrams and accurately predict the probability of different outputs for given inputs.	Correctly interpreted and predicted the outputs for all the quantum circuit diagrams.	Correctly interpreted and predicted the outputs for most of the quantum circuit diagrams.	An attempt is made, but the interpretations and/or predictions of the outputs for the quantum circuit diagrams were mostly incorrect.	No attempt is made to interpret and predict the outputs for any of the quantum circuit diagrams.

This material is based upon work supported by the National Science Foundation under award DUE-2120545. Making Nuclear Magnetic Resonance Resonate With Students: Integrating NMR Into the Undergraduate Science Curriculum,