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Challenging Disciplinary Boundaries in the First Year: A New Introductory Integrated Science Course for STEM Majors

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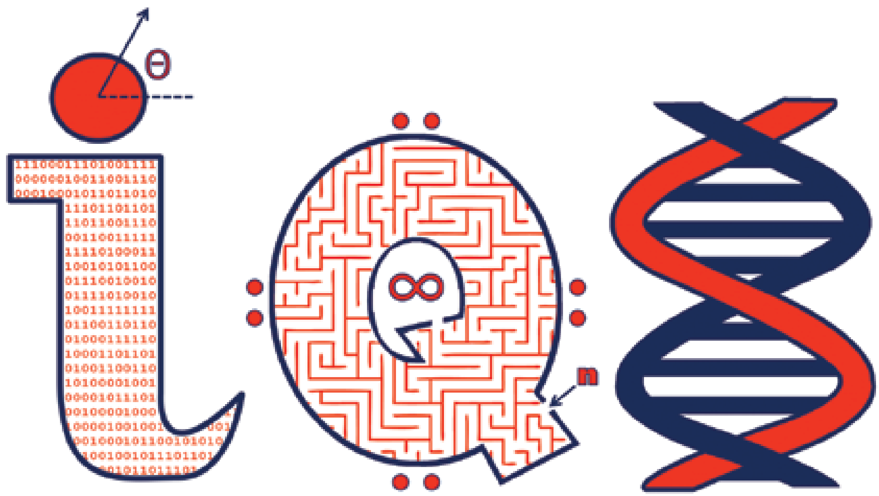
To help undergraduates make connections among disciplines so they are able to approach, evaluate, and contribute to the solutions of important global problems, our campus has been focused on interdisciplinary research and education opportunities across the science, technology, engineering, and mathematics (STEM) disciplines. This paper describes the mobilization, planning, and implementation of a first-year interdisciplinary course for STEM majors that integrates key concepts found in traditional first-semester biology, chemistry, computer science, mathematics, and physics courses. This team-taught course, Integrated Quantitative Science (IQS), is half of a first-year student's schedule in both semesters and is composed of a double lecture and a weekly lab and workshop. Features of this first-year course, including themes and concepts covered each semester, some of the materials developed, lessons learned, challenges, and preliminary measures of success are described.



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Design for the interdisciplinary course, Integrated Quantitative Science, showing elements from chemistry, biology, computer science, physics, and math.

On the basis of how many introductory undergraduate science, technology, engineering, and mathematics (STEM) courses are taught, our students compartmentalize their learning. The topics in their chemistry course are associated with chemistry and stay with chemistry; the topics in their calculus course are associated with mathematics and stay with mathematics, etc. Connections—such as deriving the integrated rate laws for kinetics using skills that were taught in calculus or understanding that nuclear magnetic resonance spectroscopy involves rotational kinematics (physics)—are often not made. For these reasons and because making progress on solving our most challenging global problems will require collaborations among multiple disciplines, we have explored ways on our campus to integrate undergraduate STEM learning. In this article we report our efforts to create and implement an introductory course that integrates five STEM disciplines.

Our initial efforts involved a three-tiered approach to introducing students to relationships between pairs of disciplines: introductory courses, mid- to upper-division electives, and undergraduate research projects (Caudill, Hill, Hoke, & Lipan, 2010). At the introductory level, we made strides in three different areas. First, two faculty members (one each from biology and chemistry) sat in on the first majors course in each other's discipline. This allowed both sets of faculty to see what was being taught, to normalize their language, to make deliberate connections, and to use examples from the other discipline. In addition, a faculty member in physics designed an alternate, second-semester general physics course, Biological Physics, which emphasized biological systems, especially in the laboratory. Finally, faculty members in mathematics developed a two-semester sequence, Scientific Calculus I and II. At the mid- to upper-division level, electives were designed and taught by faculty members in different departments and included Mathematical Models in Biology and Medicine (mathematics/biology), Bioinformatics (biology/computer science), and Biological Imaging (biology/computer science/physics).

Integration at the introductory level

To more fully integrate key concepts taught in introductory STEM courses, a group of 10 faculty (two each from biology, chemistry, computer science, mathematics, and physics) designed a new course, funded by a Howard Hughes Medical Institute Undergraduate Science Education Award, that integrates first-semester concepts in biology, chemistry, computer science, mathematics, and physics. This year-long course, Integrated Quantitative Science (IQS), consists of two units of lecture plus a weekly three-hour lab and one-hour workshop and comprises half of each student's course load. The learning goals for IQS include increased (1) interdisciplinary and disciplinary understanding of key concepts by students; (2) interdisciplinary understanding by faculty, as seen in the quality of integration in lectures and labs; (3) number of faculty in STEM disciplines equipped to create courses that draw on concepts from multiple disciplines; (4) number of students pursuing cross-disciplinary opportunities at Richmond and beyond; and (5) use by faculty of connections to other disciplines in their discipline-based courses.

A model studied closely in our design was the integrated science curriculum at Princeton University. Although one can imagine the design of many types of integrated courses (i.e., Ulsh et al., 2009), ours is constrained by the fact that students who complete it need to be ready to enter the second-semester courses in any of these STEM disciplines. We were fairly certain that our departmental colleagues would endorse our course plans if they could be ensured that key concepts in our existing first-year courses would be included. Representatives of each discipline took key concept plans (Table 1) to their respective departments for discussion and approval. Although this may have been an opportunity to have the larger discussion about competencies taught within the context of core concepts (i.e., Vision and Change in Undergraduate Biology Education, http://visionandchange.org/; AAMC-HHMI Scientific Foundations for Future Physicians, www.aamc.org/scientificfoundations) versus required key concepts, that was not our approach. Once topics were

TABLE 1

Topics that need to be included in Integrated Quatitative Science (IQS) to count as an equivalent experience to the first-semester course in each discipline.

Discipline	Topic constraints
Biology*	How modern biologists ask questions, scientific methodology, use of tools for observing the natural world, quantitative-skill building, statistical reasoning, data analysis, scientific communication
Chemistry	Kinetics, thermodynamics, equilibrium, acid-base chemistry, redox, electromagnetic radiation and Bohr model of atom, quantum mechanics, orbitals and electron configurations, bonding, VSEPR and hybridization, MO theory, Lewis structures, introduction to spectroscopy
Computer science	Fundamental object-oriented programming, conditional and looping control structures, arrays, methods and parameter passing, file I/O
Mathematics	Integration: Riemann sums, numerical estimates, fundamental theorem, substitution integrals; average and instantaneous rates-of-change, the derivative as rate-of-change, derivative and antiderivative shortcuts, linear approximations, definite integrals
Physics	Vectors, displacement, velocity, acceleration, linear and circular uniform and nonuniform motion, Newton's laws and fundamental forces in nature, work, energy, energy transfer, linear momentum, oscillatory motion, and rotational motion: cross product, angular kinematics, angular momentum, torque, moment of inertia

*The specific topics covered in biology in IQS-1 were evolution; natural and artificial selection; DNA structure, mutation, replication, transcription and translation; and prokaryotic and eukaryotic gene regulation. In IQS-2 they were cell signaling through binding of G protein-coupled receptors and receptor protein-tyrosine kinases, as well as signaling in nerve cells.

agreed on, we then focused on how they could best be integrated over the course of the year. Because our introductory biology sequence is one that focuses on the scientific process rather than specific content (Table 1), we had significant flexibility in choosing an umbrella theme for each semester, selecting "antibiotic resistance" and "communication/cell signaling" to leverage the expertise of the participating faculty and to allow for a broad range of interdisciplinary as well as the necessary disciplinary topics. At this point, our group of 10 faculty divided into two teams of 5 (one from each discipline) and worked together for a second semester to develop the course.

IQS has now been taught for two years. In the first year, the only prerequisite other than the desire to work as part of a team to integrate knowledge in these five disciplines was a course in calculus. We also tried to match the profile of the IQS class to the incoming university first-year class (gender, diversity, first-generation students, etc.). Seventy-eight students applied for the course and 20 were accepted (one laboratory section). During that first semester, we discovered the challenges inherent in the varying physics preparation of these students. In the second year, therefore, a course in physics was also a prerequisite, and 53 students applied.

IQS-1

As much as possible, each semester of IQS is set up so there are no big blocks of any one discipline (for IQS-1 and IQS-2 syllabi, see supplemental Figures S1 and S2 available online at http://www.nsta.org/college/connections.aspx). On a particular day, it may be that one or two faculty are primarily responsible for leading the discussion with others participating as appropriate.

Following are snapshots of assignments developed that focus on first-semester disciplinary topics framed in the context of the IQS-1 theme, antibiotic resistance.

- An agent-based simulation model of antibiotic resistance was developed as one of the first computer science projects. We provided much of the code base to the students and required them to implement an agent class on which the simulation relied, allowing them to implement introductory concepts—including instance variables, various methods, and parameter passing—in a context relevant to the course. Students used simple binary strings and random number generation to model antigen/antibody binding sites and were required to conduct simulation experiments with their completed model by systematically varying parameter values. For a graphical user interface of a completed agent-based simulation model, see supplemental Figure S3 (available online at http://www.nsta.org/college/connections.aspx).
- One of the fundamental skills underlying much of what is taught and learned in chemistry courses is the ability to visualize and understand molecular behavior at the atomic level. We combined computer-aided molecular visualization and simulation with modules on valence shell electron pair repulsion theory, molecular structure, molecular orbital theory, and energetic analysis to study the conformational flexibility of various antibiotics.
- In a semester-long project, students engaged in research related to the discovery of new antibiotic resistant bacterial strains from sponges. They first created cultures of marine sponges and their symbiotic bacteria. Students then exposed their cultures to antibiotic regimes that differed in their biochemical modes of action. Experiments were conducted to determine if their cultures contained bacteria that (1) were able to produce antimicrobial compounds, (2) could be cultured and identified in the laboratory, and (3) could be compared with known bacterial species with potential antibiotic producing capabilities. The last set of experiments involved cloning and sequencing 16S ribosomal DNA libraries from their antibiotic-treated cultures. Using computer programs they wrote to automate the process of searching the databases using the BLAST algorithm, students analyzed their own group's DNA sequences and made comparisons with other groups. Data was related back to the questions posed about antibiotic resistant bacteria in nature and their potential therapeutic uses. For a sample group poster, see supplemental Figure S4 (available online at http://www.nsta.org/college/connections.aspx).

IQS-2

Following are snapshots of material developed for IQS-2.

- The material for IQS-2 was focused around the theme of signaling and communication. The semester began with a five-week laboratory module that studied signaling through the toll-like receptor 4 after macrophages were activated by an inflammatory response. Students developed skills in cell culture, electrophoresis, and western blotting and also gained an understanding of ligand binding and activation of transcription factors leading to the transcription and translation of genes involved in the inflammatory response.
- The central mathematical concept in IQS-2 is diffusion, a means by which signal is transmitted from sender to receptor. Students were

asked to compare the effects of transmission by diffusion and traveling waves, using Mathematica to produce animations of the time evolution of graphs via the partial differential equations $\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2}$ and $\frac{\partial u}{\partial t} = -c\frac{\partial u}{\partial x}$. Qualitatively they saw that diffusion brings extreme values on the graph of $u(0,x) = f(x)$ closer together, whereas translation of the initial graph, according to $u(t,x) = f(x - ct)$, results from the wave equation. Later, a random walk model was used to investigate the mechanism of diffusion (Berg, 1983). Key results of this study were that (1) root mean square displacement is proportional to the square root of elapsed time, (2) Brownian motion data are computable in terms of the diffusion coefficient, and (3) the concentration at a particular location evolves to become the average of its neighbors.

- To explore one of the disciplinary chemistry topics (kinetics), a three-week module focused on HIV protease was developed. First, students determined how to measure initial velocities, explored the relationships between enzyme or substrate concentration and initial velocity (with both wild and a multidrug resistant form of the enzyme; Ohtaka, Schon, & Freire, 2003), and determined the mechanism of inhibition of two protease inhibitors. Next, they used molecular modeling to visualize the protease. The graphical user interface Maestro (available free for educational use; www.schrodinger.com) allowed students to perform mutations, changing the wild type amino acids into those of the drug-resistant form. Once energy minimized, students formed hypotheses about how the mutations affect function and binding.
- Rotational motion is the key introductory physics concept in IQS-2. To incorporate this into signaling, we used magnetic resonance imaging (MRI; Filler, 2010). This module started with a demonstration of gyroscopic motion, in close analogy with the classical description of a proton spinning in a magnetic field. Emerging questions guided students to discover the notions of angular velocity, cross product, angular momentum, and torque. The phenomenon of resonance was presented through the use of differential equation for motion of the nuclear magnetic moment under the influence of a magnetic field (Bloch, 1946). The connections to biology and chemistry were emphasized, as was a description of the fast Fourier transform, to understand the data structures and generation of anatomical images. MRI also allowed for a connection to chemistry and mathematics through the process of relaxation, which influences nuclear magnetic motion. In this way we arrived at the full set of Bloch equations (Bloch, 1946).

Opportunities after the first year

We have also designed an integrated science (IS) minor that allows students to further explore interdisciplinary approaches to science. This minor includes IQS (or each of the five first-semester courses), a sophomore-level research training seminar, research (a full-time summer research experience is available to students the summer following completion of IQS), upper-division interdisciplinary courses (i.e., Biological Imaging, Mathematical Models in Biology and Medicine, Bioinformatics, Theoretical and Computational Chemistry, Evolutionary Computing, and Systems Biology), and a capstone senior seminar. Although too early to know how many students will declare IS science minors, 79% of the first group of students that took IQS completed the sophomore-level research training seminar.

Lessons learned

Following are four important lessons that we learned during this process:

1. It was important to allow this idea to come from the faculty and to allow us to define what we needed to make it work so that we were able to also continue to pursue other academic interests (i.e., mentoring undergraduate research).
2. Allowing ample time for both development and implementation was necessary for success.
3. Focusing on group unity and community-building activities has created a cohesiveness more similar to that found in junior- and senior-level majors than in first-year students.
4. Having all 10 faculty members in the classroom during the first year of implementation was important for faculty development as it allowed us to determine ways of better integrating the materials across disciplines.

Naturally, there are challenges associated with teaching a course of this nature. One of the biggest was how to team teach in a group this large. We also had challenges associated with “full” integration of the material, especially in the first time teaching it. Part of this challenge was knowing what our colleagues were going to present, but even more difficult were the constraints on topics that had to be covered in the course (Table 1). Although biology, chemistry, and mathematics have fit well into this integrated format, physics and computer science have required a more focused effort. The University of Richmond physics department teaches all introductory classes in the Workshop Physics format (Laws, 1995, 1996; Laws, Rosborough, & Poodry, 1999), an integrated lecture–laboratory experience with inquiry-based laboratories. In IQS, however, we could not offer the integrated lecture–laboratory experience or dedicate much time solely to physics laboratories. In addition, the physics classroom environment was very traditional in the first year. In the second year of teaching, multiple changes were made to use more active learning techniques and to better integrate the material. All students were required to have some prior physics exposure so that we could cover physics topics relevant to the antibiotic resistance theme, as well as those needed as background for other disciplines. Computer science has been challenging, because only a few of the IQS students have had any prior experience in computer science. Developing assignments that focus on introductory programming concepts within the course context is difficult. Adding to the difficulty is that students must attempt to master two new concepts simultaneously—abstraction and syntax/structure of a programming language—without those concepts being the focus of IQS. Student selection for the course is also not easy. How does one best determine which students are the most interested in this way of thinking and working together?

FIGURE 1

Mean number of units that the first Integrated Quantitative Science (IQS) class of 20 students and the comparison group of 58 students who applied for IQS but were not accepted have taken in their first two years at the University of Richmond. Independent studies, academic year research, and credit for AP courses are not included.

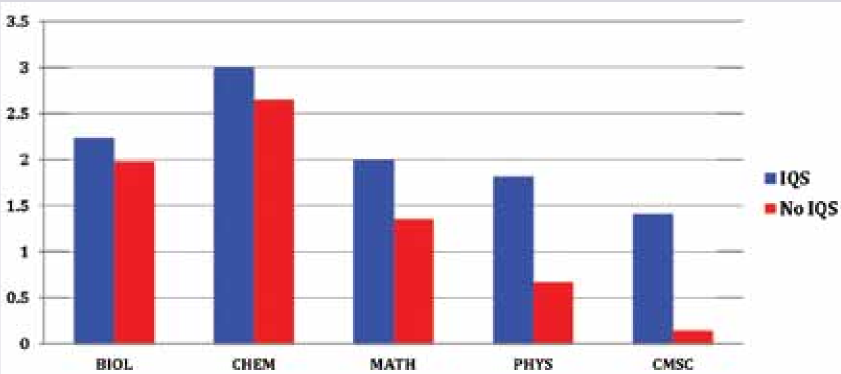


TABLE 2

Comparison of STEM experiences between the first Integrated Quantitative Science (IQS) class of 20 students and the comparison group of 58 students who applied for IQS but were not accepted.

	IQS (2009–2010)	Comparison
Number remaining at UR after 2 years	18	55
Percentage of students staying for a full-time summer research experience the summer following IQS*	100%	9%
Percentage of students staying for a full-time summer research experience the second summer following IQS	61%	22%
Percentage of students with credit for academic year research	100%	25%
Percentage of students who took a second course in one of the five disciplines	100%	88% (94%)
Percentage of students who took a second course in two of the five disciplines	94% (100%)	73% (78%)
Percentage of students who took a second course in three of the five disciplines	77% (94%)	32% (58%)
Percentage of students who took a second course in four of the five disciplines	24% (44%)	7% (18%)
Percentage of students who took a second course in five of the five disciplines	0%	0%
Percentage of students declaring a major in one of the five areas at end of the second year	94%	60%

Note: Where different, numbers in parenthesis also include research taken for course credit during the academic year, AP courses, and independent study course. STEM = science, technology, engineering, and mathematics; UR = University of Richmond.
*IQS students were guaranteed summer funding, but summer funding is easily obtained by all of our science students.

Assessment

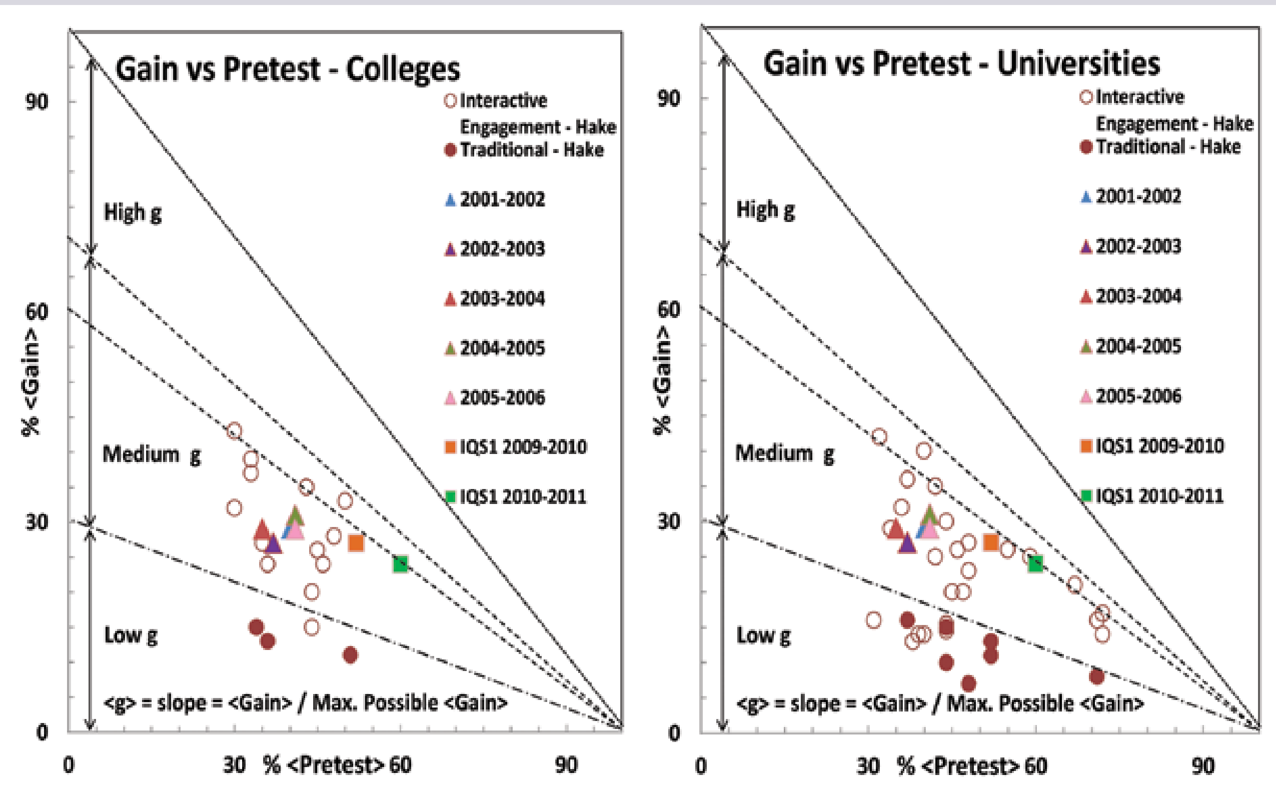
A ready comparison group for IQS consists of students who applied to take the course but were not accepted. Some comparisons on short-term outcomes between these two groups are given in Figure 1 and Table 2. In the first two years, the IQS students took (1) more mathematics and science classes on average with significant differences in computer science, mathematics, and physics and (2) more courses in more than one area, with 77% versus 32% taking the second course in the major in three of the five disciplines. It is interesting to note that only 5% of the comparison group took a first computer science course, whereas 22% of the IQS students took a second course in computer science.

In addition, to measure student perception of gains, IQS students took the RISC (Research on the Integrated Science Curriculum) survey (http://www.grinnell.edu/academic/psychology/faculty/dl/risc), which allows a comparison with students nationwide taking courses with interdisciplinary aspects. In both years, IQS students reported higher-than-average gains in presenting intellectual work in posters, working with peers from other disciplines, finding similarities/differences between disciplines, integrating ideas from two or more sciences in problem solving, studying an interdisciplinary problem, and computer modeling of complex systems.

Success in courses that build on material in the first course of the major is our primary means of measuring disciplinary understanding. To track this, at the end of each semester, we speak with the faculty teaching the next courses in each discipline to see if they have concerns about the level of preparation of the IQS students. To date, their experiences with the IQS students have been very positive. In addition, to measure learning achieved in physics, IQS students take the Force

FIGURE 2

The Force Concept Inventory test results from the more traditional setting of IQS-1 (diamonds) and the corresponding interactive engagement workshop physics classes (colored circles) are compared with a national survey of 62 introductory physics courses enrolling a total of 6,542 students (Hake, 1998) from both colleges (left) and universities (right). All of our institutional data comes from classes taught by the same instructor. Gain = (posttest% – pretest%)/(100 – pretest%). The % pretest values for the two IQS-1 classes (52% and 60%) are high in comparison with those reported by other colleges and in the top 30% of those reported by universities. IQS = Integrated Quantitative Science.



Concept Inventory test (Hestenes & Halloun, 1995; Hestenes, Wells, & Swackhamer, 1992), designed to assess understanding of basic concepts in Newtonian physics, both at the beginning and end of IQS-1 (Figure 2; supplemental Figures S5–S7, available online at http://www.nsta.org/college/connections.aspx). The difference in grade outputs, gain, is used as a measure of learning. As seen in Figure 2, this comparison places the results for the IQS classes in the upper medium–gain region of promoting conceptual understanding. Although the data suggest that the IQS-1 students are prepared as well as students that came through our workshop physics course, we are confident that their percentage gain would be in the high range if we could implement more interactive engagement activities similar to our workshop physics classes.

With respect to preliminary observations regarding the faculty-associated goals of the course, at least four faculty teaching IQS began new interdisciplinary research projects; faculty designed and added new integrated projects to the second offering of IQS; three new interdisciplinary courses have been designed for the IS minor; the faculty that started the development of IQS are still teaching in it, with the exception of one full-year sabbatical leave; and there is significant faculty interest in rotating into the teaching of IQS.

Conclusions

Over the course of the last three years, we have developed and implemented a first-year integrated science course for undergraduate STEM majors, the focus of which is on preparing students to think about problems across disciplinary boundaries. A research experience in the summer following IQS encourages students to continue to put theory into practice, and an integrated science minor provides a way for students to continue building their interdisciplinary skills beyond the first year. Preliminary observations show that by the end of their sophomore year, the IQS students are taking more math and science courses in a broader range of areas (especially computer science), have begun research earlier, and have more often declared a science major than students in a control group who also applied to take IQS. ■

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