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Research-Led Learning in Action: Development of an Online Chemistry Course for Final-Year Undergraduates

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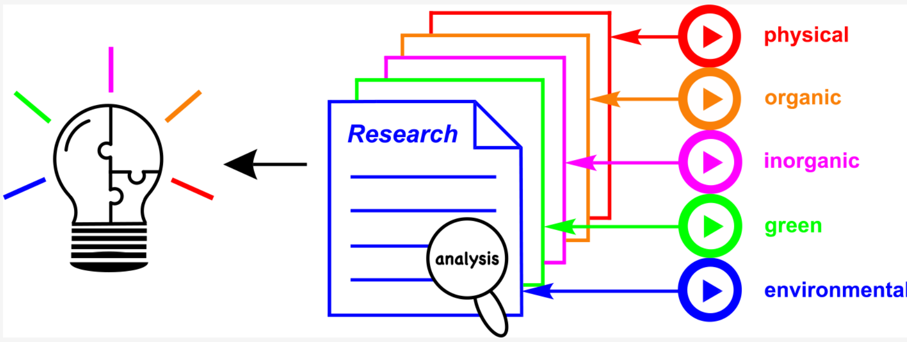

ABSTRACT: An online module for final-year master's students has been developed over a 5-year period. The module allows equitable experiences for students studying in person at the University of York, at a university abroad, or undertaking an industrial placement. Distinctively, the module was designed around the use of modern research papers, published by Chemistry at York researchers, as vehicles of information. The approach allowed students to apply chemical principles learned in earlier years of their course to the solution of problems at the forefront of five chemistry specialisms, ranging from atmospheric and environmental, to physical chemistry. Learning objectives included an appreciation of the experimental and analytical techniques used in the research, as well as the development of scientific literacy and critical thinking skills. There was also an opportunity for students to develop communication skills through an optional competition. Staff collaborated with students as partners in the development of course content, as well as establishing student workload, and testing formative assessments. Student attitudes toward the module were monitored, which demonstrated an enthusiasm for the approach and coverage of material. The flexibility to work through the content at their own pace, at a time to suit them, was appreciated by students as a whole and highlighted in disabled students' feedback. Challenges remain in engaging students to learn theoretical courses while wanting to focus on their individual capstone research projects. Assessment of students' problem-solving skills by an in-person or online examination resulted in a consistent examination performance.

KEYWORDS: *Upper-Division Undergraduate, Curriculum, Interdisciplinary/Multidisciplinary, Computer-Based Learning, Internet/Web-Based Learning, Multimedia-Based Learning, Problem Solving/Decision Making, Applications of Chemistry*

■ INTRODUCTION

Learning chemistry by integrating contemporary research and cutting-edge knowledge provides students with an opportunity to receive up-to-date information about what chemistry research is about.[1] Research skills can be strengthened, ranging from observation to analysis, interpretation of data, and library and computer skills, and students can apply theoretical knowledge. Research-led learning also provides an understanding of the social dynamics of academia and the professional world. Literature suggests that involvement in research-led learning can increase motivations for postgraduate study and/or clarify career intentions.[2] Also, student perceptions of authentic research experiences have been shown to be overwhelmingly positive.[3]

Undergraduates will be involved in research-led learning through their final-year project, typically conducted in a research laboratory. But there are several other ways in which students can experience research-led learning[4] such as case-study-based,[5] inquiry-based, or problem-based learning modes of course delivery,[6] and research-ability-focused courses, such as those involving an academic poster-format.[7] Of interest to this paper is the use of research articles in the curriculum to develop research

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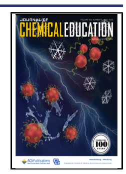

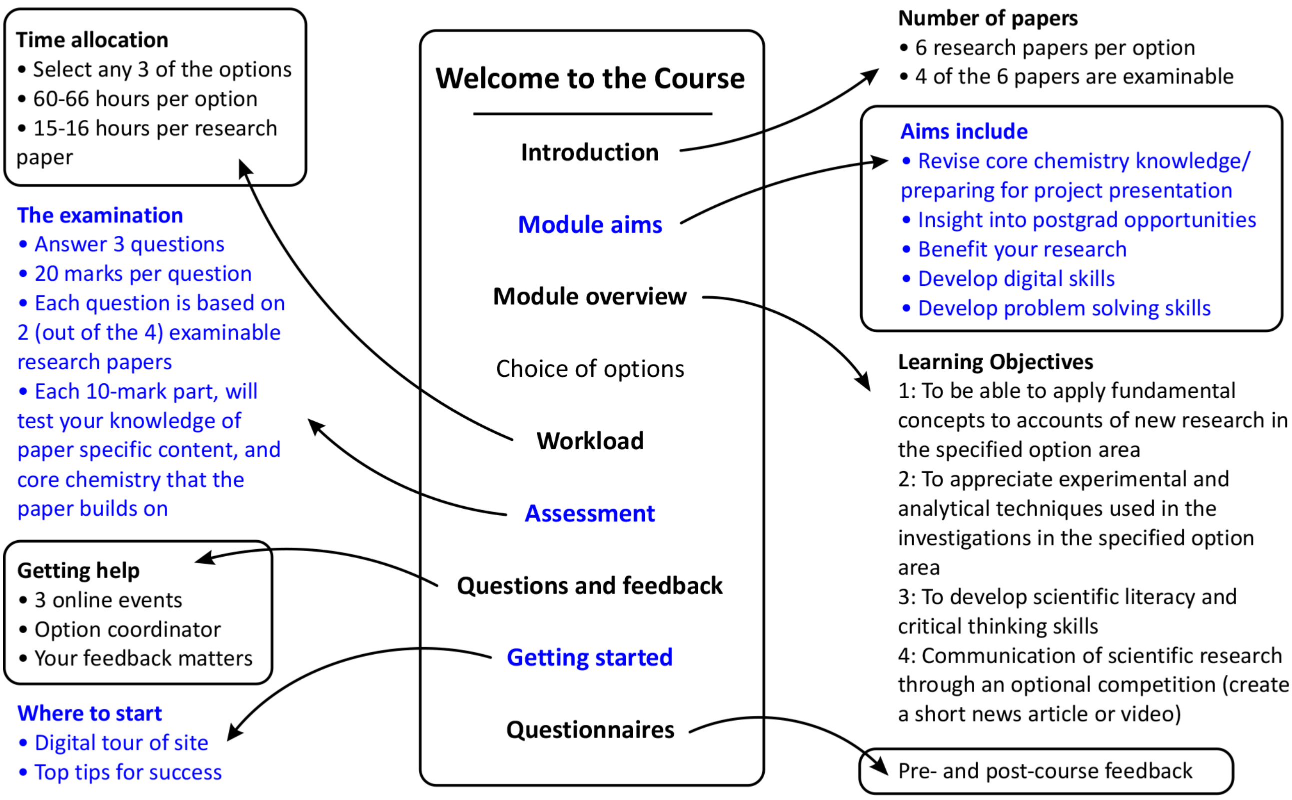

Figure 1. An overview of the introductory information.

literacy skills[8] and contextualize chemical theory covered during lectures.[9]

This paper describes the development of an innovative research-led module that ran alongside the research project for chemistry students in the final year of their master's degree at York. To the authors' knowledge, this is the first time that such an online course has been reported, together with course outcomes and lessons learned.

■ COURSE DESIGN AND OBJECTIVES

In 2016, following a restructuring of our degree courses, there was a need to design a new 20-credit (200 h) module for final-year MChem students. In UK universities, in a full-time undergraduate degree course, each academic year comprises 120 credits, which is broken down into modules that are typically worth 10 or 20 credits (where 20 credits are usually equivalent to 10 ECTS (European Credit Transfer and Accumulation System) or 5 U.S. credits). The course was required for 2021, and it was to be the sole teaching component of the fourth year. It would need to engage around 120 students who were completing their research project at York (~45 students), at a university abroad (~25 students) or in the chemical industry (~50 students). Due to the different locations, to ensure a consistent learning experience, the best choice was deemed to be a new online course, with the course materials housed on our virtual learning environment or VLE (Blackboard). The requirements of our revamped degrees meant the course needed to cover developments at the forefront of five distinct areas of chemistry, which are called "options". The options were atmospheric and environmental, green, inorganic, organic, and physical.

To meet the MChem learning outcomes, the course needed to include open-ended activities. These activities required students to apply information learned earlier in their course to consolidate and extend their knowledge and understanding of chemistry. This knowledge, obtained through taking common compulsory modules (featuring analytical, inorganic, organic, and physical chemistry) in years 1−3, is called "core chemistry". The core chemistry was taught at York using traditional lecture courses, which, depending on the year, was either delivered face-to-face or, in response to the COVID-19 pandemic, online.

Before 2021, a 10-credit course was delivered for just the year in industry and abroad students, which introduced some research-level topics, in inorganic, organic, and physical chemistry. For this course, students read through pdfs of traditional lecture-style notes on Blackboard. But there were problems with this course, ranging from inconsistencies in the time required for students to work through each topic to the fact that topics were not easily updated and refreshed (significant time was needed to produce a whole set of lecture notes). There were also few opportunities for students to test their knowledge, and this was coupled with typically mediocre to poor student feedback. So, a new, more effective and engaging online course was needed.

Beginning to develop the course in 2016 meant that it was possible to trial parts of the new course to the year in industry and abroad students. For example, in 2017, a new-style inorganic option was delivered, alongside the old-style organic and physical courses. Student and staff feedback over a 5-year period was used to gradually refine the course.

The new online course was planned with the following aims in mind:

1. To design a standard course template to ensure that the material was delivered consistently across different options, with similar student workload.

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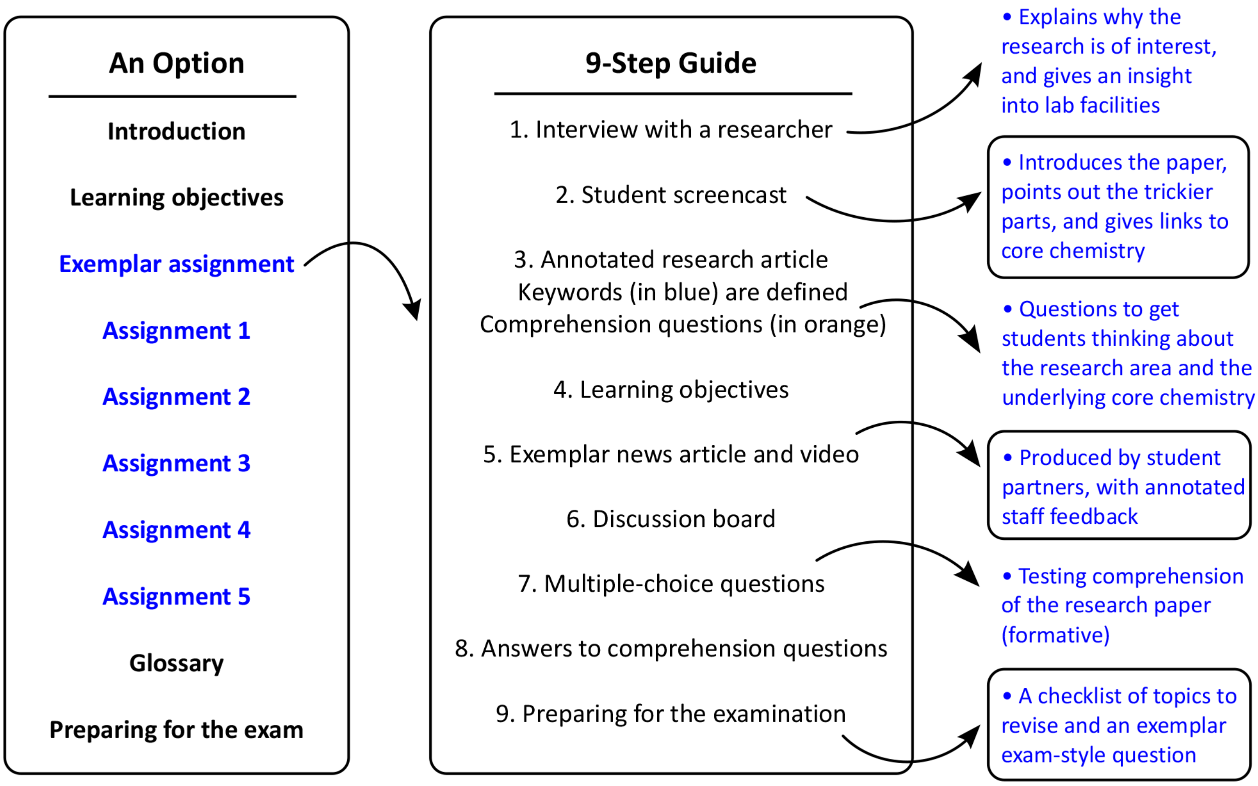

Figure 2. Components of an option.

2. To ensure the course template allowed for refreshing and updating of course material, without the need to "reinvent the wheel".
3. To base the options around recent research papers, featuring York researchers, to inspire and motivate students about modern research, helping connect them to the research of their lecturers[10] and allowing them to develop research literacy skills.[11]
4. To collaborate with students as partners in the cocreation of course materials, so that staff could understand the student experience, and develop materials which met real rather than perceived needs.[12,13]

THE TIMELINE

Following the launch of the first newly designed inorganic option in 2017 and subsequent feedback (see later), the following summer, the course was modified. At the same time, a new organic chemistry option (replacing the old-style organic course) was launched. Then in 2019, atmospheric and environmental and green options were compiled and launched, followed in 2020, by a new physical option. In 2021, the inorganic option was refreshed, and a new landing page for the module was compiled.

During each summer, staff worked with teams of 2−3 student partners, who were between years 3 and 4 of their MChem degree, typically for one month. These were paid roles which were advertised to all chemistry and natural science students (specializing in chemistry) with flexible working arrangements, and there was a competitive recruitment process. The student partners played an important role in helping cocreate some course materials, and they advised on student workload (e.g., how long it takes students to read and comprehend a research paper) and structuring course content. They also selected the papers—staff working in the relevant research areas were asked to submit papers for consideration, and the student partners picked the most appropriate ones, using criteria such as a good spread of topics and links to core chemistry, as well as ensuring participation of a diverse range of colleagues.[14] A mix of articles and communications from high-quality peer-reviewed journals were selected, and students were encouraged to read the Supporting Information. The inclusion of a review article was trialed, but this was replaced following student feedback, which indicated that significantly more time was required to read and assimilate the information than for the other papers.

The flexible course design also allows for the inclusion of courses that were based on research papers. For example, in 2019, a new sixth option in management was introduced by a colleague, which allowed students to learn about and apply different business models to chemical industry contexts.

SETTING THE SCENE

The introductory material for the online course was divided into 9 sections, starting with an "introduction", and finishing with "questionnaires" (Figure 1).

At the outset, students were made aware that they could pick any three options, five of which were based on a selection of research papers featuring York authors, and that a subset of papers would be examinable. Aims of the course were noted, including contextualizing, testing core chemistry, and helping prepare students for their research-project presentation—as part of the summative assessment of their project, students were questioned on core chemistry. The four learning objectives of the module were discussed, including the opportunity to enter a competition. Students were encouraged to create an article[15] or video[16] to describe the chemistry in their chosen research paper to a pre-university audience, thereby developing communication

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skills. The expected hours for students to spend reading the research papers and associated learning activities (such as multiple-choice and comprehension questions) were noted in a workload section. Details of the summative assessment were provided, noting that students would be tested on their understanding of the research papers, as well as the core chemistry that the papers build on. It was deemed important to reassure students that they did not need to become experts in or recall details from the research area of the paper. To show our expectations, exemplar examination-style problems (see later) and a walkthrough of an examination-style question with outline answers were provided. The walkthrough mentioned that the assessment was not testing how well students had memorized the papers—although hard copies of the research papers were not provided for the in-person examinations, if a question required students to interpret a scheme or data from a paper, then the question included this information in the preamble. Opportunities for students to get help were flagged, including contacting a member of staff who acted as an option coordinator. The importance of student feedback in shaping the course was noted, with examples of "you said; we did". Finally, students were asked to begin the course by watching a video showing a tour of the course site, then read advice from student partners on tips to succeed, based on their experiences of cocreating the course content.

THE OPTIONS

A consistent template was used for each option (Figure 2). A brief introduction included contact details of the option coordinator and identified the four research papers that had been chosen to be examinable in the end-of-module written examination. The learning objectives for the option were then given, followed by a folder containing a research paper, called an "exemplar assignment", and the remaining five papers were in folders labeled "assignments 1−5". A glossary was produced that defined key terms across papers in all 5 options, and a link to previous examination papers was provided.

In the exemplar assignment folder, the learning materials were divided into nine areas. First, students were asked to watch a short video (max 5 min), typically narrated by an author of the research paper. For all videos, to aid accessibility, transcripts were provided, and the clips could be viewed with captions, in keeping with universal design for learning principles.[17] Also, Blackboard is well structured, easy to navigate, and operable on different device types with accessibility features that allow for customization to suit individual needs (e.g., alternative formats, zooming, and customizing color schemes). The aim of the video was to excite students about the research area, explaining why it was relevant and important, and it usually showed the author's research laboratory—through showcasing their research and laboratories, staff saw this as an opportunity to encourage students to apply to their lab for postgraduate study. Next, students were asked to watch a short screencast (max 5 min) produced by a student partner that introduced the research paper.[18] The aim of the screencast was to identify core chemistry that the research builds on, as well as pinpointing the more challenging parts of the paper—by getting student partners to show how they got to grips with the paper, it was felt this would give confidence to students who felt daunted by the research area. For a few papers, some underlying concepts were not covered sufficiently in year 1−3 core courses. To support these topics, learning resources were prepared (a pdf and/or screencast, with links to further reading).

Next, students worked through a pdf of the research paper, which was annotated with definitions of key terms and comprehension questions. These questions were designed to get students thinking about the work presented in the paper, such as the methods used (e.g., why were these chosen?), the importance of the results (e.g., is the work novel?), and the underlying core chemistry (e.g., how were the yields calculated?). For each of the four module learning objectives (Figure 1), a detailed set of sub-objectives were provided—for example, under learning objective three, subobjectives highlighted the specific analytical techniques, and experimental procedures, that students needed to be aware of after reading the exemplar paper. To encourage students to enter our competition, news articles and videos were created by student partners, which were annotated with staff feedback to identify good practice and areas for improvement when producing material for a preuniversity audience. For each option, students were encouraged to post questions and observations on the research papers on a discussion board (they could do this anonymously), to get feedback from fellow students and the option coordinator. To help students test their understanding of the research and get immediate formative feedback, a bank of multiple-choice questions was compiled by staff and tested by student partners. Students could attempt these questions as many times as they liked, with different sets of questions appearing on different attempts. Once students had satisfactorily answered 50% of the questions, they were given immediate access to outline answers to the comprehension questions. If they did not complete the multiple-choice questions, the outline answers were provided around two months prior to the examination. Finally, a checklist of revision topics was provided, which detailed the specific core chemistry topics that students needed to revise prior to the examination, together with an exemplar examination-style question and outline answer.

For assignments 1−5, the same learning resources were provided as for the exemplar assignment, apart from the news article and video. For the competition, students were expected to pick any research paper from assignments 1−5 as the basis for their article/video, so exemplars were not provided. To prepare for the end-of-module examination, students needed to work through the exemplar assignment and the three selected assignments (chosen by the option coordinator, and varied year on year), and a question would test students' knowledge of any two of these assignments.

A key advantage of creating a series of self-contained assignments was the ability to easily refresh the content e.g., after four runs of the inorganic option, two papers were replaced with newer ones. The design also allows assignments to be moved around, into different options, i.e., the assignments can be reshuffled, like a deck of cards.

ASSESSMENT OF COURSE OUTCOMES

Student Feedback

The outcomes of the module were assessed using different methods, including through optional student pre- and postcourse questionnaires, designed to gauge opinion anonymously and for no credit. Students accessed the electronic questionnaires through Blackboard, and they were designed to gauge student feedback and allow instructors to adjust the course. The precourse questionnaire, to be completed after working through the introductory information, asked students about their motivations for choosing their three options and

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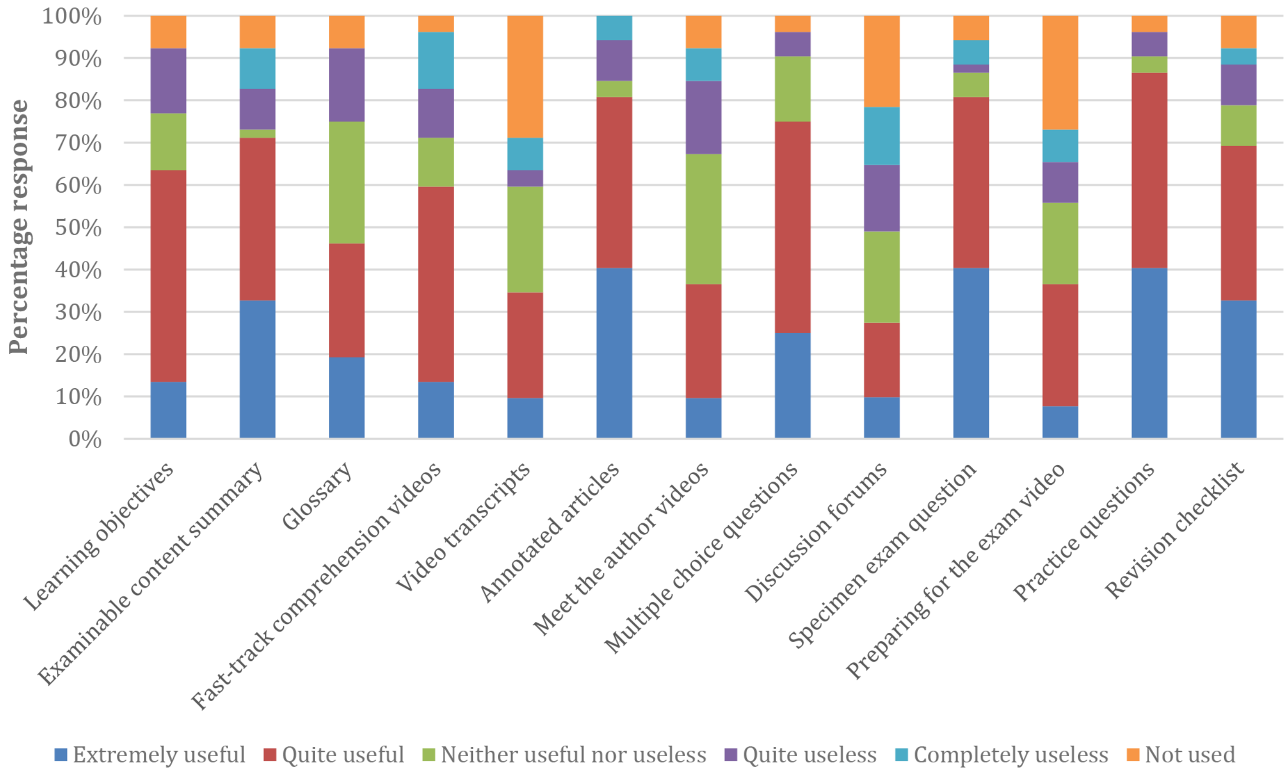

Figure 3. Stacked bar chart showing the responses from end-of-course feedback surveys for courses running in 2020−21 (N = 33) and 2021−22 (N = 19).

probed their knowledge of chemistry research within the department. Students typically picked options that aligned to their final year research project and/or linked to lecture courses that they had enjoyed in earlier years of their degree. Most students could identify one or two areas of research expertise. For the postcourse questionnaire, after reading through the research papers, students typically gave a more wide-ranging set of examples. Indeed, a common enjoyable aspect of the course, identified in the student feedback, was the opportunity to learn more about research conducted at York. One student noted that they enjoyed "reading about all of the research going on at York and linking it to what we have been taught and maintaining a broad appreciation for chemistry." Another commented that "some of the papers were really fascinating" and the course was a "good opportunity to get practice at reading beyond the area of my project."

Gradually introducing the options over a 5-year period gave the opportunity to reflect on significant student and staff feedback to refine, reshape, and improve the course. For example, for the first run of the inorganic option (in 2017), positive postcourse student feedback was received like "a very well delivered course with excellent supporting material", "great resources and innovative delivery of course", and "the breadth of available resources and clear organization made navigating it very easy". Coupled with this critical comments were also received, particularly relating to the assessment, such as "not always clear what to take away from the papers," and "good concept, but the examinable content could be more explicitly stated." This feedback instigated the revision checklists, which identified the specific core chemistry topics for each paper. The feedback also included comments like "could have not read the papers and still answered question," which reflected more emphasis in testing core chemistry principles over an understanding of the research paper. This point was echoed by another student who said, "overall, I enjoyed the module and found it interesting, but I felt the exam mostly tested my core knowledge rather than the papers." To ensure a more balanced spread, specific examination question guidance was provided to staff and students—this noted an expectation that for each question, around half the marks would be assigned to questions testing core chemistry and the other half testing comprehension of the paper (see later). Also, the 2021−22 feedback asked for additional resources to help students revise core chemistry knowledge from previous years, so a series of practice questions and outline answers were produced—these covered interdisciplinary topics (such as calculations, symmetry, and orbitals).

Following course changes, part of the optional electronic feedback survey asked students to evaluate the different features of the course using a Likert-style response scale, ranging from "extremely useful" to "completely useless". The percentage of each type of response for the courses running in 2020−21 and 2021−2022, with data from 52 of 240 students (22%), is shown in Figure 3. The "practice questions" had the best response with a combined score of 87% for "extremely useful" and "quite useful", followed by 81% for both "annotated articles" and "specimen exam question", then 75% for "multiple choice questions", and 71% for "examinable content summary". Reported advantages of formative assessments, for example, as tools for students to separate topics they have mastered from those they have not, no doubt contributes to their popularity in this course.[19] The surveys also asked what aspects of the course students enjoyed, and developing literacy skills, learning about research at York, and having the flexibility to work around their research project were the most frequently mentioned. For example, one student noted "I really enjoyed getting to read a range of papers and get a detailed understanding of completely

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different topics. I also feel it really accelerated my scientific literacy skills." The feedback also showed that some students based in the chemical industry found it challenging to fit the course around their industrial placement workload (placement companies were encouraged to allow time for students to work on the course during the working week).

During the pandemic some students noted that they did not know how to make good progress on the course, and they were reluctant to use the discussion boards to ask for help—a constant challenge has been getting students to engage with the boards, despite staff regularly adding threads and the option for students to post anonymously. In response, for the 2021−22 course, the introductory material was revised (Figure 1), giving more guidance on how to read a research paper effectively and critically,[20,21] and three online meetings hosted by staff were introduced. The online sessions were also aimed at encouraging students to start working on the module early in the academic year (occasionally, students were found to focus too heavily on their research projects and began the course much too late) and enter the competition. (Each year less than 2% of the cohort submitted competition entries; for example, in 2021−22, four students submitted an article and two submitted a video.) For those unable to attend to meetings, recordings were made available. The sessions proved effective in getting more students to post questions on the discussion boards (from around 50 posts per year, this increased to 200). The increased student engagement was also reflected in the feedback survey; for 2020−21 the "discussion forum" had the worst response with a combined score of only 6% for "extremely useful" and "quite useful", but for 2021−22 this increased to 63% (Figure 3). Students were also given the opportunity to ask questions at the online meetings—for the second and third meetings, questions were mainly about the assessment, from checking the format of the examination to asking about effective ways to revise core chemistry (peer-to-peer learning was encouraged). There were also concerns about workload, which also appeared in the written feedback from students in 2020−21, such as "I was unable to fully explore and understand each paper, and area of chemistry, to a significant extent in order to get through all the papers, and then revise the relevant content". Following student and staff feedback, it was realized that the expectations were too ambitious at the outset of the project, namely, expecting students to work through 18 research papers (6 per option). Hence, for the 2021−22 course, this was revised to 12 (4 per option) and students were allocated 15−16 h per paper (Figure 1).

Summative Assessment

The summative examination was designed to test if the learning objectives had been met—it tested students' understanding of the research papers and their knowledge of core chemistry. The examination paper included a 20-mark question for each option, and the marks from the three questions chosen by the student were totaled to give an overall mark for the 20-credit module. Each 20-mark question was divided into two 10-mark components, which asked questions on the two examinable research papers selected by the option coordinator. Each 10-mark component was subdivided, approximately equally, between questions testing an understanding of the research paper and those on core chemistry topics linked to the paper.

During and prior to 2019−20, students sat a 2 h in-person examination. In 2020−21 and beyond, this changed to a 5-h online examination (during which time students needed to upload their answers to Blackboard). This assessment method was also aligned to the goals of the learning and teaching, i.e., to develop students' problem-solving skills and ability to apply core chemistry to new research problems rather than assessing memorized knowledge. Using research papers as vehicles to test knowledge was well-suited to an open-book online examination, developing students as scientists by assessing research skills.[22] Questions were placed in novel contexts so students could not find answers by searching the names or structures of compounds on the Internet (see Supporting Information). As open-ended questions were employed that asked for proof and justification in answers, students needed to apply their knowledge through analysis and critical thinking. Assessing chemical reasoning not only makes the assessment more authentic, but it can also support diverse groups of students to achieve.[23] The examination was not proctored—students had access to the research papers and their lecture notes and could consult other resources such as using a calculator and accessing the Internet. A paragraph on academic integrity was included at the start of the examination paper, which was publicized to students ahead of the examination. It made clear, for example, that the work submitted must be entirely their own and, for the whole time the assessment is live, that students must not communicate with other students on the topic of this assessment. No evidence of academic misconduct was identified by the markers.

Pleasingly, the questions on the different options scored similar averages, typically within ±10%. Student performance on the research paper focused versus core chemistry questions was also broadly comparable. Between 2018 and 19 and 2021−22 the average overall mark for the examination was over 60%, indicating a good student performance on the module. For example, over four years, the organic option scored an average mark of 66%. Interestingly, the examination averages proved reasonably consistent whether the examination was conducted in person or online, perhaps due to the assessment focusing on testing problem-solving skills over bookwork. The average examination marks (between 2018 and 19 and 2021−22) varied by only around 5%. For example, for the online examinations, the 2020−21 overall average mark was 4.5% higher than for 2021−22. One contributing factor to the increased mark could be due to the inclusion of additional practice questions. This was supported by the results of the postcourse questionnaire—when students were asked to rate how they felt the course materials prepared them for the assessment, the satisfaction rating increased by 12% for 2021−2022 compared to the previous year. However, as the course content had been reduced (from 18 to 12 research papers) and two different groups of students completed the examinations, other factors could be at play.

■ CONCLUSIONS

This distinctive online course allowed students to connect with recent research work of their lecturers. Research papers provided excellent vehicles to contextualize and test core chemistry knowledge. It was pleasing to see the positive student feedback noting how this course helped students see opportunities for postgraduate study. This project demonstrated the positive impact that student partners can make in cocreating course materials, and the authors were grateful for the enthusiastic engagement of research colleagues who appreciated the benefits of showcasing their research to prospective postgraduates. The structure of the course has allowed content to be easily updated, with relatively little effort needed to introduce new papers at the expense of others. As the number of options and associated

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research papers can easily be changed, this online course template could find use in different capstone courses, with varying credit values. Also, the flexibility of the course design allows students based in research groups spread around the globe to work through the material at their own pace, at a time to suit them, thereby providing an inclusive approach to support diverse learners.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c01207.

Sample revision checklist, multiple-choice questions, comprehension questions and an examination-style question and outline answer (PDF)

Sample introductory researcher video clip (MP4)

Sample student screencast clip (MP4)

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Notes

The authors declare no competing financial interest.

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