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Activity

A Murder Mystery Gamification Session to Consolidate Analytical Biochemical Techniques Learning

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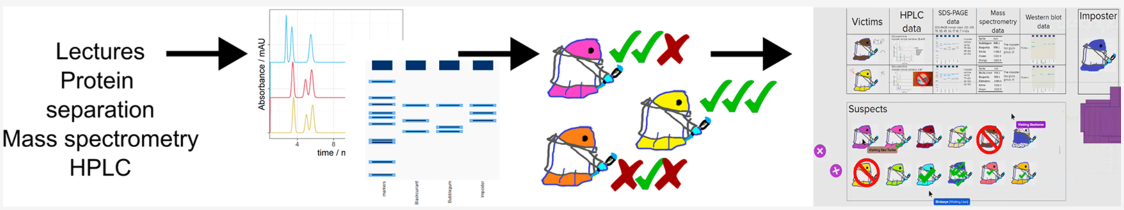

ABSTRACT: Gamification has a strong track record of improving student engagement and learning in the chemical sciences. Meta-analyses of different approaches to gamification have highlighted that providing a game fiction, encouraging students to work in teams, and breaking games into smaller "quests" are particularly effective. Here, we aimed to increase students' engagement and learning with four analytical biochemistry techniques (high-performance liquid chromatography, sodium dodecyl sulfate polyacrylamide gel electrophoresis, Western blot, and mass spectrometry) by creating a game that required them to use every method to solve a "murder mystery". Our game was based on the popular games "Mafia" and "Among Us" and introduced an original game fiction relevant to our setting. Students attending the formative gamified session gave highly positive feedback. They indicated that they enjoyed the session and increased confidence in the methods involved. Free text comments praised many of the elements deliberately introduced into the game. To our surprise, the main criticism was that the session was not challenging enough. We developed a revised session that required students to undertake more detailed data interpretation, which students reported gave the expected increase in difficulty. All materials and code for running our session and generating new mysteries with original data are available online.

KEYWORDS: *Gamification, Second-Year Undergraduate, Upper-Division Undergraduate, Biochemistry, Multimedia-Based Learning, Bioanalytical Chemistry, Student Engagement, Humor/Puzzles/Games, Problem Solving*

■ INTRODUCTION

The use of game concepts in education is attracting increasing attention.[1] Games and gamified learning can be used to directly teach educational concepts, can provide behavioral improvements (such as students' motivation, engagement with taught material, and attitude to learning),[2] and can act as a vehicle to improve social cohesion within a group of learners,[3,4] helping them to cooperate in other tasks and develop a positive learning environment. Moreover, a sense of wonder is a key reason many students and staff were first excited by science.[5] Educative play can help to reinvigorate students' sense of joy and awe in their study.[6]

Game-based learning is theoretically divided into the use of *serious games* and *gamification*.[7] Serious games are discrete, stand-alone games that have an educative purpose. The act of playing the game is sufficient to impart learning without additional instruction. Many researchers have developed games for chemical and biochemical education. Examples include card games to aid memorization,[8−12] quiz games,[13,14] board games with chemical challenges,[15−21] escape rooms,[22−30] narrative games,[31,32] murder mysteries,[33,34] and the use of ChemDraw as a game.[35] Game writing has been used as an educational tool,[36] while Lego[37] and Lego Serious Play[38] have been used to teach scientific concepts.

Gamification, in contrast, takes some or most of the elements of a serious game.[7] These are used to provide the educational, behavioral, or social benefits of games to a class or even an entire course.[39] However, the class or course will still include some traditional instructional aspects or moderation. The gamification adds value to the education rather than providing the education itself. Meta-analyses of high-quality gamification studies have shown that well-designed gamification results in significant, positive effects on cognitive, motivational, and behavioral learning outcomes.[1,40] The approaches that contribute most to educational outcomes are breaking activities into missions or "quests", having students work in teams (especially competitively against other teams),

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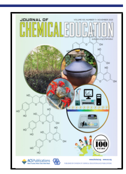

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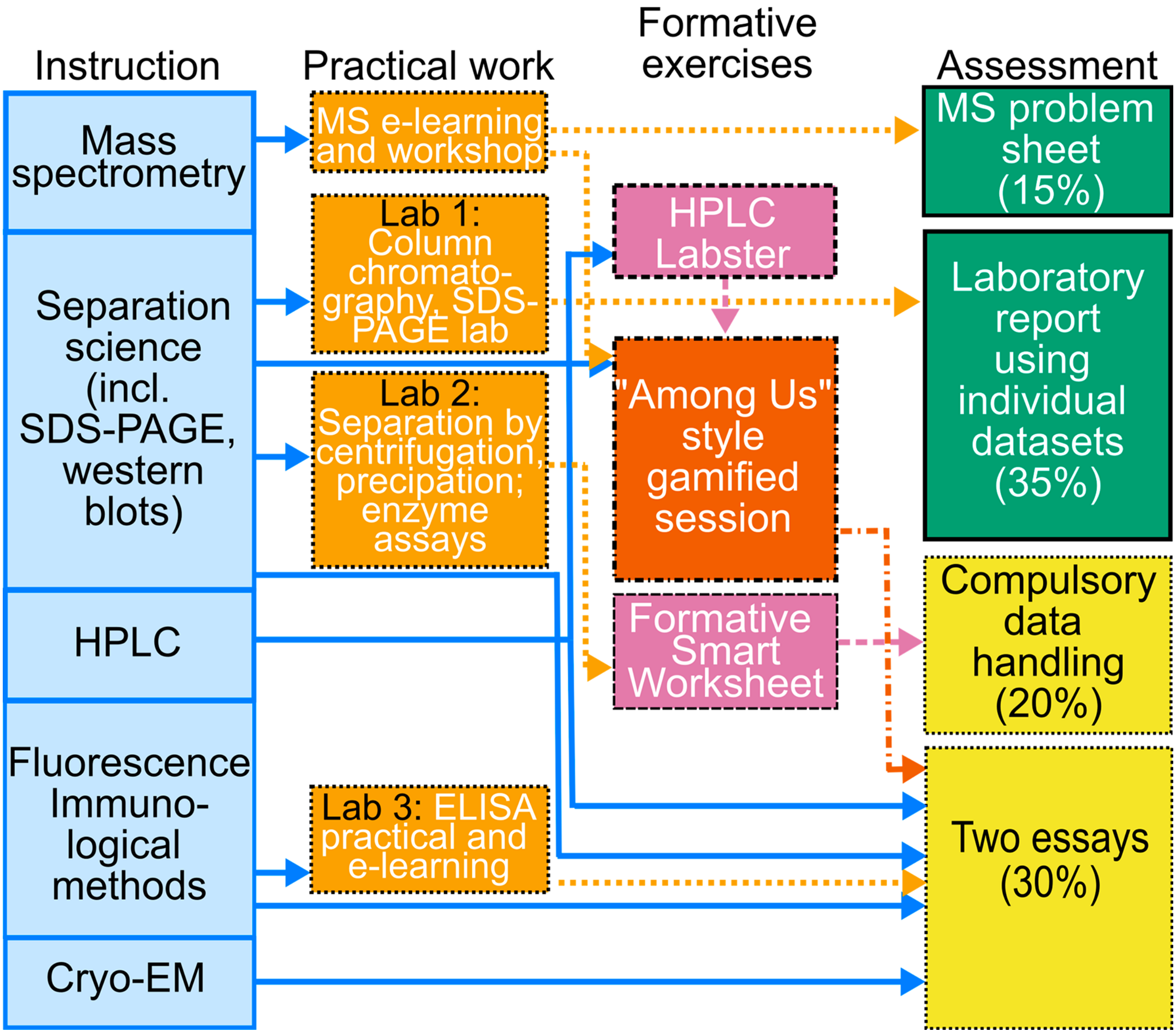

Figure 1. Overview of our "Analytical Techniques in Biochemistry" module. Students are instructed on material in five blocks (left, sky blue, solid outline). The block size reflects the timing and quantity of material. These instruction sessions support four workshops and practical classes (orange, short dashed outline). Students were previously provided with formative exercises in data handling (via a "smart worksheet") and HPLC (pink, long dashed outline); this work reports on an additional formative session (red, alternating dashed outline) that integrates several areas taught in the course. These sessions support student summative assessment (right) through coursework (green, solid outline) and an examination (yellow, dashed outline). The examination requires students to complete a compulsory data-handling section based on practical classes and to answer questions on two of the four taught topics (separation science, HPLC, fluorescence/immunological methods, and cryo-EM). The fluorescence and cryo-EM sections were not selected for the gamified session as they had not been fully delivered before the point in the course where this session could be accommodated. ELISA: enzyme-linked immunosorbent assay.

giving responsive feedback, and allowing customization or personalization of the game.[1,40] Including a game fiction also showed a positive impact on learning behavior.[1,41]

We decided to introduce a new gamified session into a second-year module to reinforce student learning and encourage student collaboration and problem-solving skills. The aim of the session was to help students to integrate their understanding of the course material, as we had observed that many students compartmentalized their study and lacked a broader context.[42−45] Second-year students at the University of Exeter in the Biochemistry and Biological and Medicinal Chemistry degree programs take a compulsory module in "Analytical Techniques in Biochemistry".[46] Students study biological mass spectrometry (MS), separation sciences (including high-performance liquid chromatography (HPLC)), fluorescence techniques/immunological methods, and cryo-electron microscopy (cryo-EM; Figure 1). We planned our gamified session to cover the mass spectrometry, HPLC, and separation sciences aspects of the course. Our course examination (Figure 1) requires students to complete a data-handling section based on practical classes and answer questions on two of four topics from the course (separation science, HPLC, fluorescence, and cryo-EM). Our gamified session therefore covers two of the four elective topics, and students have in the past found these more intimidating.

SUMMARY OF CHALLENGES

Our goal was to provide an activity that would require students to integrate their knowledge of four specific techniques that had been taught in the course (mass spectrometry, HPLC,

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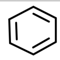
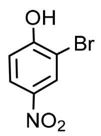
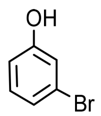
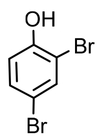
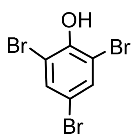
sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE), and Western blot). Specifications for the session included the following: data provided should be sufficiently simple for students to interpret within a class; a full "mission" should take approximately 20 min (allowing for two missions in a 50 min synchronous session with responsive feedback); missions should be best undertaken by a collaborative team; students should have an interactive interface to the session (to allow a competitive-collaborative situation); and the session should have a narrative to add to student engagement (as these last three points are shown to improve engagement).[1,40,41]

We wanted to develop code to underpin our class that could automatically generate new randomized missions of different difficulty levels. This made design of the final class far easier as we could rapidly explore different levels of challenge. It also facilitated providing a video with a simple example and further examples for students to complete after the class to encourage continued learning and challenge. To make the class plausible, this required code to automatically generate realistic data. Several good models of HPLC have been published.[47−50] We found that the Fasoula and colleagues' model[48] was most easily generalized and adapted to our class. For simplicity, we selected five compounds from their study with divergent properties to better illustrate HPLC principles (Table 1[53−58]).

Table 1. Chemicals Used in the HPLC Experiment[a]

Name and CAS No	Structure	Molecular Weight (Da)	cLogP [b]
Benzene 71-43-2 [53]		78.11	2.1[54]
2-Bromo-4-nitrophenol (2B-4NP) 5847-59-6 [55]		218.00	2.4
3-Bromo-phenol 591-20-8 [56]		173.01	2.6
2,4-Di-bromophenol (2,4-DBP) 615-58-7 [57]		251.90	3.2
2,4,6-Tri-bromophenol (2,4,6-TBP) 118-79-6 [58]		330.80	4.4

[a]Data obtained from Pubchem.[59] [b]cLogP values for compounds other than benzene were computed by XLogP3 3.0 (PubChem release 2021.05.07)[60] using the hydrophobic parameter[61] from the experimentally determined value of phenol.[54]

Although the mathematics of SDS-PAGE and the resultant Western blots are well described,[51,52] we were not able to identify straightforward code to generate realistic looking gels or blots. We therefore wrote this code for our simulation. We decided that interpretation of mass spectra would be too challenging in the limited time available and so provided only m/z data to analyze.

■ OVERVIEW OF THE SESSION

Scenario

We chose to structure our scenario in a similar style to the popular social game "Mafia"[62] (effectively deployed in the online game "Among Us",[63−65] which many students had played during its popularity peak in late 2020).[66] "Among Us" is a murder mystery with otherwise identical characters, where one is a murderer (referred to as the "impostor" hereafter). Rather than the social interaction approach of these games, the students in our session were provided with cycles of data giving clues to the identity of the impostor by a facilitating instructor. In every cycle, students received one experiment from each of the four methods used in the session, performed on a subset of the suspects and an impostor sample. The instructor then invited students to indicate which suspects they thought most likely to be the impostor and which suspects they thought were very likely innocent. After either two or three cycles (depending on difficulty), student teams were asked to vote for the suspect they considered to be the impostor, who was then revealed. The instructor discussed the task (highlighting the most challenging data interpretation and process of working out the impostor) to provide feedback. To make the mission more challenging, a small percentage of data were replaced with "tampered" results (with a set "error rate" of 4−10% depending on the difficulty of challenge intended). Part of our goal was to help students appreciate that real data can be contradictory or confusing, that experimental repetition is important, and that all data must be considered with caution.

To integrate the methods that we wanted students to develop skills in, we developed a narrative (Supporting Information) of abstracted creatures ("lab sprites") whose characteristics we had full control over. These creatures were identified only by a range of nontraditionally named colors[67−69] as most people across different cultures prefer these, and it reduces the risk of participants having negative associations with certain colors.[70,71] In the scenario, these creatures themselves perform the experiments whose results the students interpret. This justified the inclusion of contradictory data, as these are assumed to have been doctored by the impostor. The narrative premise included that these creatures would be assisting in the students' capstone projects in the following year, giving them an incentive to identify the impostor.

Data Provided to Students

Before the session, students were provided with a briefing document that included the game narrative, a description of the experiments to be used, data on HPLC samples (Table 1), data to interpret the Western blot and MS results, and a suspect chart to aid deduction. Students were also provided with a video walk-through of a simple example mission. Students were provided with four pieces of data in each cycle (Figure 2). Variables that altered mission difficulty were the proportion of suspects covered in each data set and the error rate. A "moderate" mission consisted of two cycles of data, with 12 starting sprites and a 4% error rate. A "standard" mission had 18 starting sprites, a 6−7% error rate, and three cycles, and a "hard" mission had 24 starting sprites, an 8−10% error rate, and three cycles of data. In the class we tested moderate and standard missions. Analytical HPLC data on impostor and suspect samples showed the presence of two or three of the five compounds in each sample. Using the published model,[48] samples varied in both mobility in the

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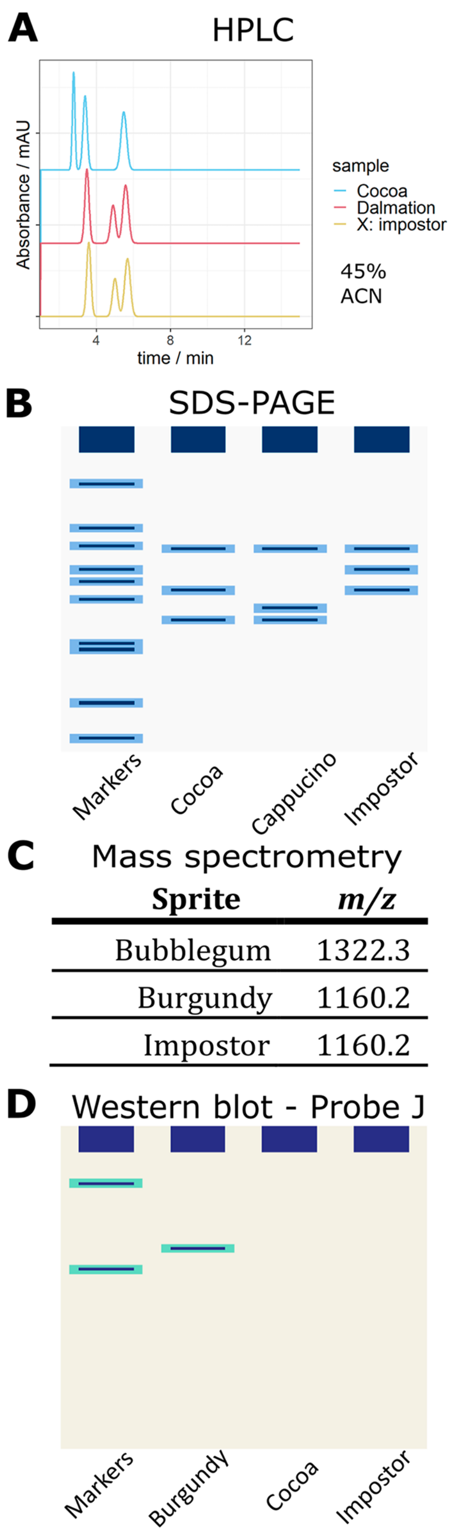

Figure 2. Example of one data cycle given to students in the first iteration of the session. Students were given each of these four pieces of data (A: HPLC; B: SDS-PAGE; C: mass spectrometry; D: Western blot) at 90 s intervals. This example is for an example game with six suspects (one of whom has already been eliminated), a low error rate, and data provided for the impostor and two suspects at each data point. This can be set up using the "easy" *R* script. The SDS-PAGE gels and Western blot shown here are simplified images suitable for students with less scientific background. More realistic images for science students are shown in Figure 5. ACN—acetonitrile; the other solvent is water.

column and relative absorbance. SDS-PAGE data showed the presence or absence of five discrete proteins, one of which was expected to appear in all samples. A reference lane allowed students to relate different gels to one another. The mass spectrometry and Western blot data were to be interpreted together to assign one of six possible "glycosylation patterns" (analogous to the human ABO blood groups; see the Supporting Information) to each suspect. Students were provided with an ascertained mass of suspect glycans and with Western blots detecting one of the constituent monosaccharides.

Game Flow

We deployed the session in a teaching room using the visual collaboration tool Mural.[72] This tool allowed students to interact with the data on their own devices independently while simultaneously releasing the latest piece of data to the whole class. Teams were able to use this to interactively highlight their likely suspects and make their final deduction. Each mission had a separate Mural page with all clues and the solution uploaded before the class, with covers that only the class instructor could remove. Each cycle started with a new victim being revealed, as in the original "Mafia" game.[62] Students then received the results of one of each type of experiment. For each cycle (Figure 2), results were revealed one experiment at a time, with a delay of 90 s to allow teams to process data. At the end of each cycle, students were invited to identify current suspects of interest in the Mural display using either crosses or ticks. At the end of the final cycle, teams had 1 min to finalize their chief suspect. The solution was then revealed (Figure 3). The class leader discussed interpretation of data to provide feedback following each cycle and particularly at the end of the mission.

Ethical Issues and Approval

We considered the ethical issues surrounding this session. A pre- and postsession questionnaire was provided to students (Supporting Information). Key issues considered were the collection of anonymous student feedback using Mentimeter,[73] briefings given to participants, participants' consent to data collection, data use (in this study), and data management. Our application was peer reviewed by expert colleagues and approval granted by the University of Exeter Department of Biosciences ethics committee.

Mural names anonymous users as a "visiting [animal]" (example: sky blue arrow pointing to "Visiting Seahorse", Figure 3) to give individuality while maintaining anonymity, although users can alter this name (example: red arrow pointing to "Birdseye (Visiting Lion)", Figure 3). Some students added their own more frivolous annotations as they were learning to use Mural (e.g., left of Figure 3 panel B).

■ STUDENT EXPERIENCE AND FEEDBACK

The session proceeded very effectively. Student attendance was optional (as is the case for all sessions in "lecture" format at our institution; all sessions including these were recorded and made available to all students). Attendance and the group of attendees were similar to other sessions in the module. All the students attending (21 in the academic year 2021/22 cohort and 38 in the 2022/23 cohort; out of total classes of 82 and 100, respectively) brought their own devices as requested to allow them to interact with and process data as they wished. Students self-organized into groups of two or three (although one student in each cohort attempted the session alone). We

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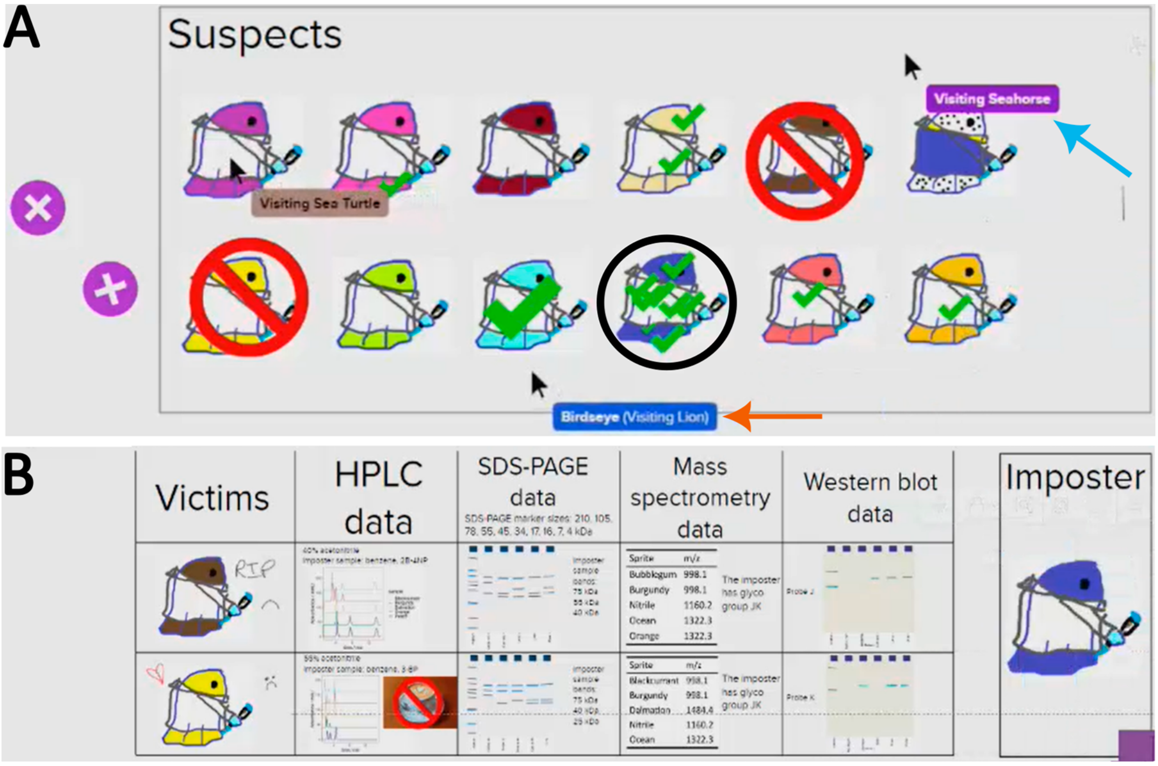

Figure 3. Example of game flow. (A) After each cycle of data, students were invited to indicate their preferred suspect using tick symbols (for a likely suspect) or crosses for a suspect unlikely to be the impostor. The red symbols indicate "victims" who cannot be the impostor. The example shown is for the "moderate" mission version, after the second cycle. Here, students have indicated their preferred suspect (Ocean Sprite, fourth from the left, lower row, black circle). (B) Final outcome of the moderate mission (same mission as panel A). All data have been revealed, and students have indicated their choice. This was indeed the revealed impostor (right of image).

observed that students divided tasks between them in a group, with each student taking responsibility for one piece of data. They then shared their interpretation with the group, often using the suspect chart provided in the briefing document. The online technology selected (Mural[72] and Mentimeter[73]) worked entirely as intended. The instructor had used both tools previously but did not require specific training in either as they are comparatively intuitive. Alternatives to Mentimeter include Slido,[74] Poll Everywhere,[75] Kahoot!,[76] or Microsoft Forms[77] and Miro[78] or Lucidspark[79] for Mural. Our students were experienced in using Mentimeter from use across modules in their program of study. Students reported that they had not used Mural before this session. Use of Mural was demonstrated in the presession video, and students were encouraged to experiment with it before the session. Students rapidly learned to use Mural and quickly worked out how to view and interpret the data. For the first cohort, in the first (moderate/two cycle) mission, almost all groups correctly identified the impostor (18 of 19 responders). In the second (standard/three cycle) mission, approximately 80% of groups correctly identified the impostor. In both cases, the identity was not clear until the final cycles (as the facilitator had anticipated). Students were clearly interpreting the data effectively as their intermediate suspicions were appropriate to the data available.

Before the session, the first cohort of students (2021/22) reported that they felt moderately confident in the techniques used (Figure 4). Their main motivations for participating in the session were to have fun (five responses out of 21), to apply their knowledge (three), and to consolidate understanding (three). Half reported that they had not read the briefing document, 25% had read this somewhat, and 25% had read thoroughly. Following the session, students reported that they had enjoyed it, felt more confident in their understanding of the methods presented, and would like to see more gamified sessions in the future (Figure 4).

In free text responses, students highlighted that they liked the following: the element of fun in their learning (which improves student motivation for learning),[82,83] working in teams, the interactive nature of the session, the interactive tools used that preserved anonymity, and the element of data ambiguity to replicate real science (Table 2). They reported that the mild time pressure enhanced their experience. Students gave several suggestions for improvements. They generally felt that the session could have been more challenging. A particular issue raised was that the data could be interpreted by pattern matching with a limited understanding of the methods. This could be a positive element of the class for less specialized audiences (for example, we have had interest in using this session from our forensics class aimed at law students). Students suggested that requiring interpretation of the HPLC and SDS-PAGE data to match impostor data provided in a different way would add to their experience. Students found it unnecessary to interpret the mass spectrometry and Western blot data as they could rely on pattern matching. Again, providing the impostor data in a different way to be matched could make the experience more authentic. Finally, students suggested that the SDS-PAGE and Western blot data could be made less perfect (e.g., less

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Figure 4. Student responses to questions. Students were asked to rate their enjoyment of the session, confidence in the techniques involved, and enthusiasm for similar sessions. Answers were requested on a five-point Likert scale. Questions were posed in the session slightly less formally using Mentimeter. Student answers were captured in the session except for the question "Today's session was fun" for the 2022/23 class which was captured in the following session due to an issue with data capture. Images prepared using *R*[80] and the HH package.[81]

effective loading, gel "smiling") to align with their experiences in practical laboratories.

In response to these comments, we designed an amended script to provide a more challenging session for (bio)chemistry students (Supporting Information), while the original session would be appropriate for students studying a different major. As students suggested, the impostor results have been removed from the figures and are provided as text results (chemicals observed; SDS-PAGE masses; apparent "blood group"; Figure 5). This requires students to interpret the results from each experiment using the skills taught in the module: students must show awareness of how molecules separate in HPLC and SDS-PAGE and how Western blots are interpreted and interpret MS data against standard values. The difficulty can be readily managed by providing fewer data points in each experiment, increasing the number of suspects, or increasing the rate at which doctored data are reported. The SDS-PAGE and Western blot scripts have been updated to improve image quality and allow options for band intensity to vary with protein amount added.

We then repeated the session in the amended form with a following cohort (2022/3). Before the session, students reported similar reasons for wishing to attend the session, with "fun", "revision/consolidation", and "understanding HPLC" being the most common responses. In this cohort, 21% of students had not looked at the briefing document, 58% had looked somewhat, and 21% had looked thoroughly. The level of confidence in the techniques for this larger cohort was lower (Figure 4). Following the session, the level of confidence gained was lower, with more students reporting reduced confidence. This perhaps reflects students overestimating their understanding until the need to apply this revealed their need for further study, which would be a positive outcome pedagogically. Students again reported that they enjoyed the session and would like more gamified sessions. The second cohort's free text responses suggested that they found that the increase in challenge had been too great and that the time given to work out the answers was not sufficient for the more challenging iteration. Following the student feedback, we intend to run future sessions in a longer class with a more extensive briefing to help students engage. The response rate to the in-class survey was lower for this cohort as a substantial proportion of the class had a following class to attend some distance away and left during the survey.

■ LIMITATIONS

We note some limitations that were apparent in this activity as currently implemented. The sample size of our class data is limited and suffers from both attendance at the class and completing the questionnaire being optional. The shorter session resulted in some students not being able to provide postsession feedback in the 2022/3 class which reduced the confidence that we have in this cohort's feedback. One question was also not captured during the session and had to be asked in the subsequent class, further reducing confidence in this feedback. The delivery differed between the two years in response to year 1 feedback, leading to response differences between the two groups. It is difficult to assess increases in the students' understanding of the methods as no comparison in ability was performed before and after the class. We have observed that it is challenging to run the session within our standard 50 min classes: a longer session is likely necessary for learners to fully benefit. Course leaders must estimate the capabilities of their class when choosing how challenging to make the problems, adding a challenge to delivery of the activity. Finally, instructors will need some proficiency in *R* to make significant alterations to the script (e.g., altering the experiments used or adding extra elements to personalize the class); the script author has moderate proficiency in *R*.

■ DISCUSSION

We developed a "murder mystery" session to help students gain confidence in their skills in analytical biochemistry using the popular game "Among Us" as an inspiration. The gamified session showed strong success, as students reported that it developed their understanding and confidence. Students reported a strong increase in their confidence in understanding the four methods presented. Students also reported that they enjoyed the session. We considered the session to have been a clear success, having been both enjoyable and effective in achieving the session aims. An important advantage of the game approach that we took over "Among Us" style games is

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Table 2. Student Feedback from Session (2021/22 and 2022/23 Cohorts)

Student Comment (Number of Responses)	Educator Response (Where Necessary)
2021/22 Cohort (14 of 21 Students)	
Liked the teamwork element (3)	
Liked the time pressure (3)	
Liked the element of fun (4)	
Liked the interactive session (2)	
Liked the ambiguity in data that makes more options possible (1)	
Found Figure 1 in the manual irrelevant (1)	We have amended the session for (bio)chemistry students, providing different information on the "imposter" data so that students are required to interpret data using Figure 1 in the game briefing.
Suggested to make the SDS-PAGE harder to interpret for realism (1)	We have amended the SDS-PAGE script for bioscientists to make it more challenging to interpret.
Could be improved by making the HPLC key clearer (1)	This has been corrected in the code released with this manuscript.
Enjoyed the opportunity for an interactive session while maintaining anonymity (1)	
Require more interpretation of the SDS-PAGE gel	We have amended the session for (bio)chemistry students to require more interpretation of the SDS-PAGE gel.
Make the session more challenging (2)	For future runs we will increase the difficulty level by including more possible sprites and a greater level of errors.
2022/23 Cohort (12 of 38 Students)	
Liked the element of fun (3) and appreciated the effort	
Suggested slowing the session (3)	We will run future sessions over 90 min rather than 50 min to give more time.
Found the HPLC difficult to analyze in the time (3)	Extra time will partly be used to give more time for students to interpret HPLC in the more challenging sessions.
Suggested talking through the instructions at the session start (1)	Future sessions will have a longer briefing, using the extra time.
Found the session a great revision tool (1)	
Was disappointed at getting the wrong answer (1)	
Suggested putting the suspect names under their image in the suspects gallery (1)	This is an excellent suggestion, and we will do this in future sessions.
Student admitted not preparing for the session and so found it harder (1)	

that all students were involved in the game throughout, and none had to play the role of the "impostor". This allowed all students to focus on the data analysis aspects of the class. It also makes the class highly scalable, with 38 students playing simultaneously and a clear capacity to further increase this.

In developing our session, we followed many of the recommendations given by experienced gamification experts[84] and those identified in meta-analyses.[1,40] We developed an original game fiction to increase student motivation: this also provided a vehicle to customize the scenario presented to methods that are important learning outcomes for our module. Our session was divided into separate "missions" to allow students to engage for a discrete period (12−20 min), with a break in between missions. Our session can be tuned to match the length and difficulty of missions to the session length and student skill. We asked students to work in teams of two or three (which they generally did enthusiastically), with teams able to indicate their suspicions after each data cycle to give an element of competition. The Mural platform allowed students to do this anonymously, and they were aware from the briefing document and presession video that all their responses would be anonymous. From our experience, this encourages students to engage. We also provided feedback during and particularly after each mission to validate correct student choices. The major proven gamification approaches that we did not use were customization and personalization (e.g., allowing students to use their own symbols or avatars in the Mural or having personalized feedback on deductions provided through Mural).[40] These would be challenging to implement in the context of our session; our primary aim was ensuring the success of the session. Now that the session has proven successful, we would consider allowing groups options for customization in future iterations.

We noted some key learning points from unstructured feedback that our students gave to improve the session (Table 2). First, students felt that the session as originally run was not sufficiently challenging. We had chosen the scenarios to be clearly solvable but not straightforward. However, we had perhaps erred too far on the side of ensuring that students could achieve a correct answer. The students expressed that some elements of the session were repetitive. They felt that the data structure could be altered subtly to require a higher level of interpretation to address this and the challenge of the puzzle. Adding some novelty to the tasks required would help maintain student interest throughout the session. We were heartened by the student comments that they would have welcomed a more challenging game and reflect that we should have the confidence to challenge our students more. The code available online includes an optional update where greater interpretation of data is necessary. However, from our second cohort, we found that the level of challenge needs to be balanced carefully against the time available to solve the problems.

Students in both classes gave text feedback on the session. Some raised more than one point. Many of the responses praised elements of the session that we had deliberately included. These comments are in line with previous studies.[40,84,85] Several students raised excellent suggestions

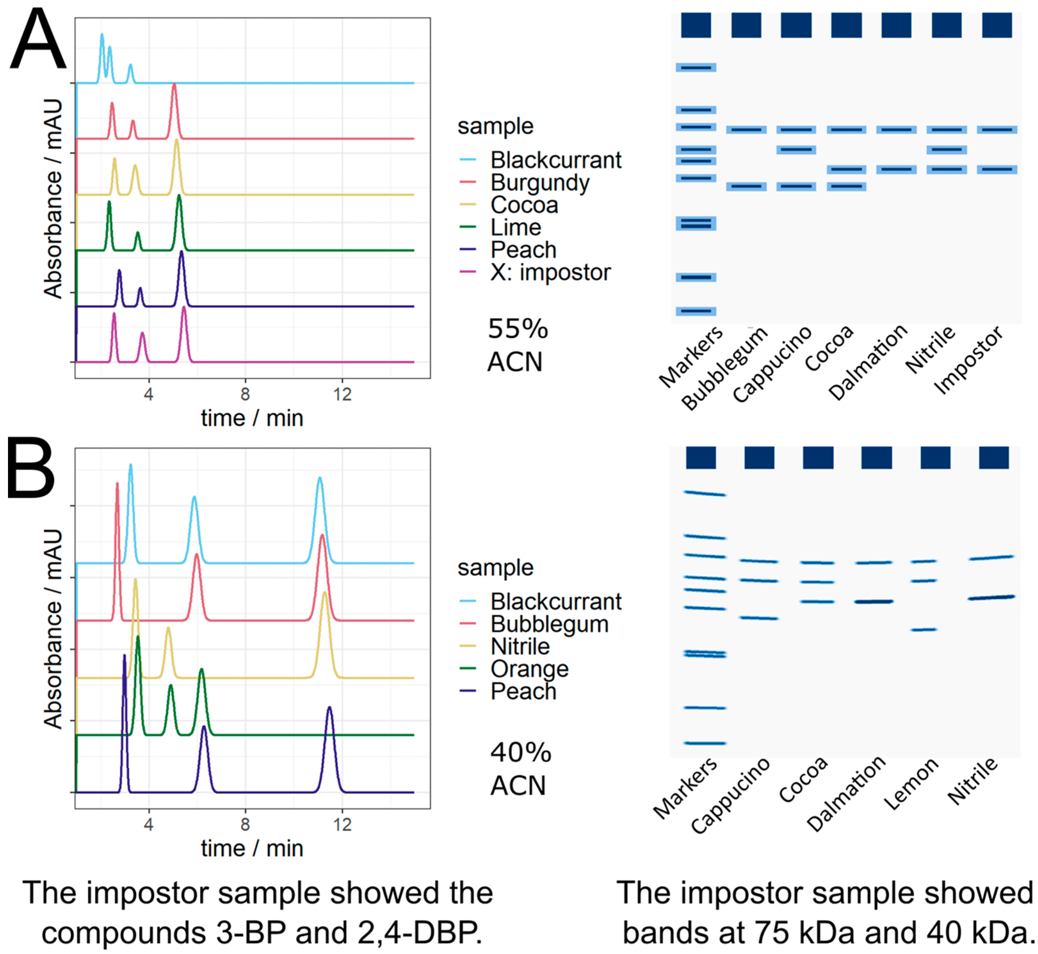

Figure 5. Session material was modified in response to student comments. Student feedback suggested that they preferred more realistic and challenging material. The original material is shown in panel A for comparison. Panel B shows the modified material. For HPLC, the impostor sample was removed, and students were instead provided with the identities of two compounds from the impostor sample. This requires more interpretation, especially for the compounds with similar clogP values. For SDS-PAGE (and similarly for Western blot), the code was extended to make the gels less "perfect": well width and center incorporates error to reflect aberrant loading, and a "smile" was introduced with a random extent. Greater load of some bands was also introduced. The impostor sample was again removed, and students were given the size of two proteins from the imposter sample. This again requires students to show interpretation of the gel. While more challenging, this should be possible relatively quickly for students who have prepared appropriately, which was supported by student feedback. We would recommend that the SDS-PAGE gels of the type in panel B are used for science students as they are more realistic. ACN = acetonitrile; the other solvent is water.

for improving the session (e.g., requiring students to perform more interpretation, expanding the briefing in the session). We have made amendments to the code to implement these suggestions. Some of these suggestions would make the session inaccessible to nonbiochemists (e.g., forensic science students): consequently, we have separated the code into two streams for biochemists and others. We intend to ask a student to assist us with changes for future implementation to provide a student perspective before the session.[86]

A final student comment was that the game was more immersive as aspects of the module taught by three different staff members could be integrated. As we aimed to make this a standalone session rather than part of a gamified course,[39] we reflected that a session like this is best held toward the end of a module to synthesize more content. We will consider for the future whether this session could be used as a review session for the whole module. This would allow a greater range of data types to be included to increase the novelty and interest of the exercise. We would recommend to others seeking to use a similar approach to schedule a session toward the end of the module.

■ SUMMARY AND OUTLOOK

We report here that a gamified session successfully reinforced students' understanding and confidence in interpreting data from a coherent set of experimental laboratory methods. Students reported that the session was helpful and fun, while providing clear feedback on how to improve such sessions. We believe that the concept we have used here could be readily adapted to a wide range of experimental methods. Indeed, it could also be applied to nonscience subjects such as law to develop student skills in interpreting and integrating data. Adapting the narrative to suit course material would retain the immersion aspects of the session. Important elements of our session to maintain are the ability of teams to work together with an element of competition between them, breaking activities into discrete "missions", and providing contemporary feedback. Our study particularly shows the benefits of using a gamified session for synoptic integration of content from a module to highlight students' ability to apply their understanding of related concepts together. We encourage others in

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the sciences to use the best practices of gamification to enthuse and educate students.

Code Overview

The game generation code was developed in *R*, as the main code writer had most experience in this language. *R* has been used by others successfully for chemical education applications,[87] but other languages such as Python could also be used.[88,89] Our annotated *R* scripts (Supporting Information) provide an explanation of each step. These can be used to replicate the session or adapt it for other experiments. Writing the initial code was onerous (approximately 30 h of work): much of this time was spent testing output difficulty, on an aborted alternative approach to the HPLC simulation, and developing the code for SDS-PAGE and Western blots. Scripts improved following student feedback are also provided. We expect that these scripts could be reused or repurposed with limited additional investment. Scripts were written in *R* v4.2.1,[80] RStudio 2022.07.1 Build 554. Five nonstandard libraries were used: tidyverse v1.3.2[90] (an excellently supported package supporting data manipulation), ggplot2 v3.3.6[91] (an excellently supported and easy to learn graphics package), rcartocolor v2.0.0[92] (to provide colorblind-friendly color palettes), elliptic v1.4-0[93] (which provides mathematical functions for the SDS-PAGE gel), and kableExtra v1.3.4[94] (provides table functions for the output file). The scripts should be used in the RStudio desktop environment, as this provides access to another package (pandoc) that is not found in standard repositories.

■ ASSOCIATED CONTENT

Data Availability Statement

A video explaining the scripts and giving an example of use can be found at (https://youtu.be/zfCNjB2KYDQ). *R* scripts are also available from GitHub (https://github.com/njharmer/Biochem-murder-mystery). *R* scripts can be run through a web browser at CodeOcean (https://codeocean.com/capsule/8095683/tree/v2). Users should read the packet metadata before running.

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00279.

> Contents document; Zip file containing *R* scripts with an appropriate folder structure; Annotated *R* scripts; Game briefing document; Questionnaire; Example problem sets of varying difficulty (ZIP)

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Notes

The authors declare no competing financial interest.

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