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Analysis and characterization of student interactions in a remote laboratory: Measurement of the enthalpy and entropy of vaporization of *n*-octane

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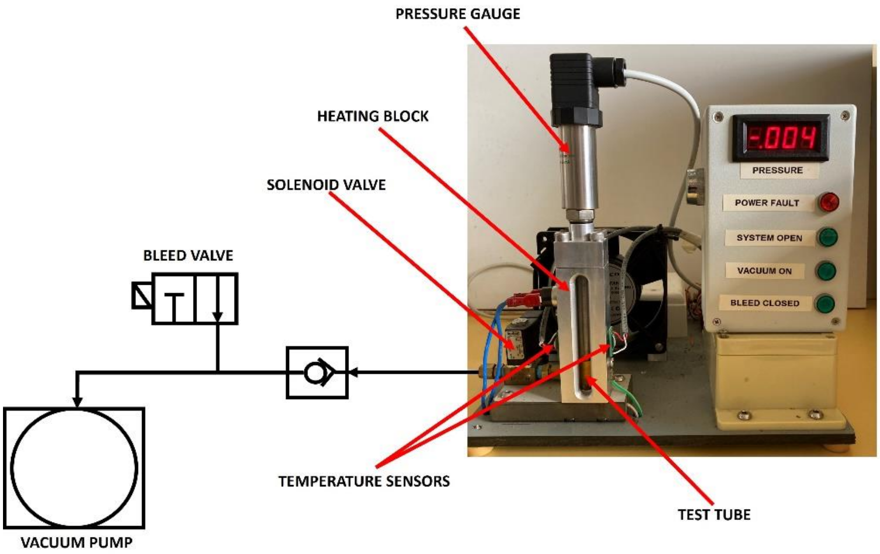
ABSTRACT

A remote laboratory that measures the enthalpy of vaporization ($\Delta H^\circ_{\mathrm{vap}}$) and the entropy of vaporization ($\Delta S^\circ_{\mathrm{vap}}$) of n-octane was designed, constructed, and offered to second-year physical chemistry undergraduates at the University of New England (UNE) and Curtin University. The experiment was delivered in real-time, using equipment controlled remotely via the Internet. A survey instrument was developed to investigate the learning process from the students' viewpoint and was followed by focus group interviews. Guidance from the laboratory manual and from the visual hints available through the webcam was important for their learning and was used most frequently among all the interactions. The students were satisfied with the laboratory and would like to perform other remote experiments. Types of learning interactions, such as experiment construction and technical skill learning could be partly achieved with support from technicians and the meticulous design of online guidance.

GRAPHICAL ABSTRACT



KEYWORDS

Second-year Undergraduate, Physical Chemistry, Internet/Web-Based Learning, Distance Learning/Self Instruction, Thermodynamics

INTRODUCTION

The outbreak of the Covid-19 pandemic has had a significant impact on the instruction of laboratory courses resulting in many institutions converting these traditionally face-to-face teaching formats to online ones.[1] Among changes to the instructional methods and delivery platforms have been the need to provide alternatives to face-to-face science laboratories. The research reported here on a remote laboratory is part of a larger study (see Wei et al. 2018 for details).[2] This report preceded the current pandemic and was driven by financial and collegiate considerations for remote laboratory sharing between universities, as well as to explore the learning benefits, and turned out to be fortuitous timing.

Laboratory learning has long been thought to be an important aspect of chemistry learning. [3-5] For laboratory learning, having sufficient equipment for experiments is an essential and integral component. According to the latest available data in Australia, there are presently around 121,980 students enrolled in engineering and related technology degrees and 94,602 in natural and physical science degrees.[6] As Australian universities are experiencing an increasing number of undergraduate students, there are growing demands for laboratories and especially the need for more equipment. One solution to this demand can be the use of simulated or remote laboratories as a supplement or replacement for the traditional laboratory. Sharing remote laboratories between different universities can allow for the optimal use of apparatus and therefore can be economically sustainable.[7, 8]

Remote laboratories are characterized as mediated manipulation, meaning that there is a geographical separation between the learners and the equipment, sometimes also a separation from the other learners, and/or the instructors. Even though data are obtained from the students' manipulation of equipment, the work is mediated through computers and the Internet. The delivery of actual experiments in real-time can provide a deeper understanding of the concepts because students can undertake the experiments at the time of their choosing, there are no time restrictions, and each experiment can be repeated many times. In this way, remote laboratories can be an important and viable supplement for face-to-face laboratories and provide students with close-to-authentic experiences, especially for those laboratories that are unsafe or inconvenient to implement. Laboratory sharing between different universities can also compensate for other universities not all having expensive equipment.[9] With the increasing use of remote operations in industries, training in the use of remote laboratories in universities is important for preparation for future employment.[10]

There is an increasing number of remote access laboratory projects worldwide, both in engineering and science subjects. The Weblab at the University of Cambridge has been set up since the late 1990s and the remotely controlled chemical reactor lab has been one core part of the Chemical Engineering curriculum at Cambridge.[9] The iLab Shared Architecture (SAPULA) is an international project between the Massachusetts Institute of Technology and several other universities.[11] Also the BC-ILN program provides convenient chemical analysis remote laboratories at Thompson Rivers University in British Columbia in Canada.[12]

The increasing use of technology presents a quandary for institutions of higher education. On the one hand, learning technologies have provided the possibility for instructors to teach many geographically dispersed learners both in synchronous and asynchronous modes. On the other hand, a reliance on technology does cause a change in the learning environment and experience. For example, the learners may undergo a reduction in unexpected situations and a lack of direct experience of uncertainty that in traditional laboratories are addressed by scaffolded learning.[13]

This study is an initial step in introducing a remote laboratory and testing its application from the perspective of students' viewpoints. An instrument was designed to collect students' perceptions, from three aspects: Student Interactions, Student Opinions (Authenticity and Flexibility), and Student Satisfaction.

Interactions are among one of the most influencing factors for laboratory learning. Many factors, such as the student's background knowledge; interactions with equipment, laboratory manuals, computers; the demonstrators' instructional style; and their objectives for conducting the laboratories, may influence students' learning outcomes.[14, 15] However, based on the theory of constructivism, learners can only build their knowledge through interactions with the environment[16] or with other people.[17] Therefore, the functions of interactions in laboratory learning should not be diminished.

For a remote laboratory, the interactions can be as follows: Student-Student Interactions, referring to the interactions between students; Student-Internet Interactions are those interactions when students are searching through websites; Student-Lab manual Interactions are those interactions when students are using the laboratory manual; Student-Instructor Interactions are those interactions between students and instructors (if there are any).[18]

Additionally, students' opinions of the remote laboratory, including authenticity and flexibility, were included in the survey. Even though the remote laboratory is designed to be an authentic process, it is doubtful whether the students have the same opinions as those of the designer. The physical separation between the students and the equipment (sometimes with the instructor too) in a remote laboratory is assumed to influence the learning outcomes.[19] This separation might decrease the students' opinions on the authenticity of the laboratory process, and influence the students' overall satisfaction with the remote laboratory consequently.[20, 21] On the other hand, one of the most significant benefits provided by remote laboratories are their flexibility when considering laboratory space and students' schedules.[10]

According to a commonly employed model for describing an individual's acceptance of information systems - the Technology Acceptance Model, beliefs and attitudes are the primary determinants of whether or not the technology could be adopted by learners.[22] In this model, perceived usefulness and ease of use are two common features. These variables are combined with other factors, including the quality of the remote laboratory, the willingness to try other remote laboratories, and the overall satisfaction, as Student Satisfaction in this project.

Therefore, this study attempted to assess the effects of technology and laboratory learning from the aspect of students; the research questions that guided this work were:

1. What type and range of frequency of interactions do students engage in during the remote chemistry laboratory?

2. What do undergraduate students consider to have been important interactions after the completion of the chemistry laboratory?

3. How do the undergraduates describe their satisfaction with the remote chemistry laboratory?

4. How does the frequency of interactions, student opinions, satisfaction variables, and overall student satisfaction correlate in the remote chemistry laboratory?

DESCRIPTIONS OF THE REMOTE LABORATORIES

The Experiment

Accurate vapor pressure data for volatile organic hydrocarbons, such as n-octane are required when modeling industrial chemical reactions in the vapor phase that produce energy or target chemicals.[23] Applications of automotive and aviation fuels and many catalytic processes need these data to achieve optimum performance. The liquid and vapor equilibrium for n-octane is

$$\mathrm{C_8H_{18}}(l) \rightleftharpoons \mathrm{C_8H_{18}}(g) \tag{1}$$

Vapor pressures, P of n-octane are a function of temperature and are dependent on the enthalpy, $\Delta H^{\circ}_{\text{vap}}$, and entropy of vaporization, $\Delta S^{\circ}_{\text{vap}}$, by the Clausius-Clapeyron equation:

$$\ln \frac{P}{P^\circ} = \frac{-\Delta H^\circ_{\mathrm{vap}}}{RT} + \frac{\Delta S^\circ_{\mathrm{vap}}}{R} \quad (2)$$

Here, P° is the standard pressure (1 bar). Vaporization is an endothermic process, while at the same time system entropy increases. Equation (2) assumes that both $\Delta H^\circ_{\mathrm{vap}}$ and $\Delta S^\circ_{\mathrm{vap}}$ are independent of temperature and do not allow for entropy change maximization.[24] By measuring P over a range of constant temperatures and then plotting $\ln P/P^\circ$ against $1/RT$ an approximately linear relationship results with slope $-\Delta H^\circ_{\mathrm{vap}}$ and intercept $\Delta S^\circ_{\mathrm{vap}}$.

The learning outcomes of this remote experiment are:

- Understanding laboratory procedures that enable the measurement of accurate thermodynamic data
- Understanding the Clausius-Clapeyron equation
- Skills of scientific inquiry: collecting and interpreting data, testing hypotheses, drawing conclusions, and communicating the method and outcomes
- Collaborative learning and teamwork

The online experiments, named as *SmartLab*, are located in the School of Science and Technology at UNE and can be controlled and monitored by enrolled students from anywhere with internet access. A webcam stream and live data are continuously updating the user webpage and guide students through the experiment. Experiments can be done at any time, without booking, although access is denied if another student is using the experiment.

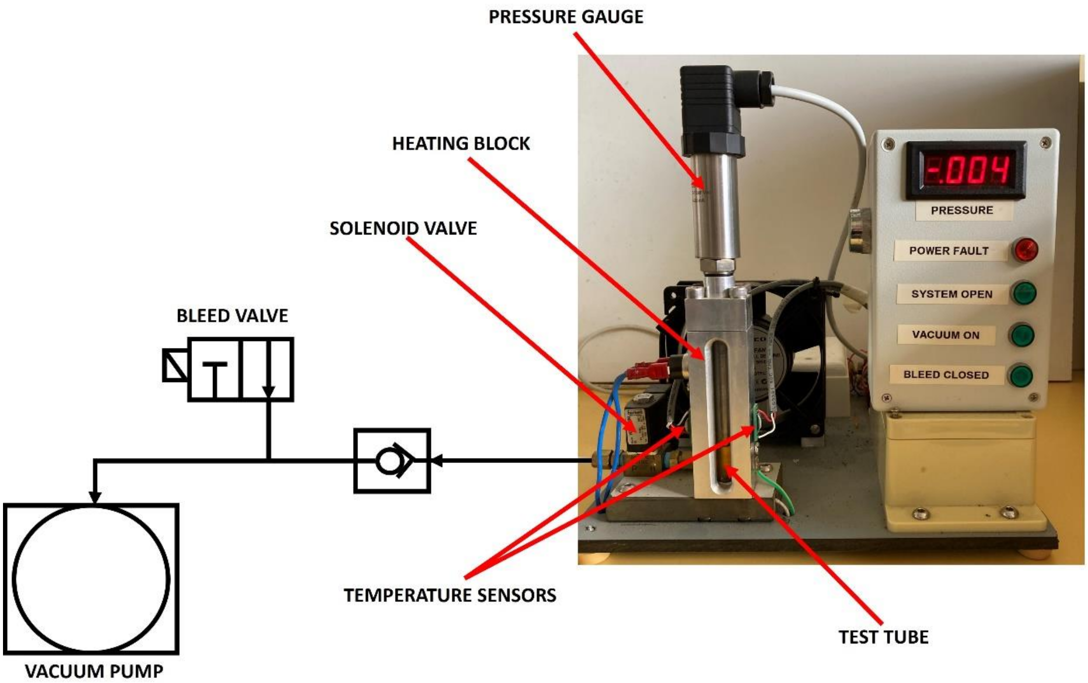


Figure 1. Schematic diagram and photograph of the vaporization experiment.

Figure 1 is a schematic diagram and photograph of the remote, vapor pressure experiment. Liquid *n*-octane is in a test tube surrounded by a heating block, an aluminum block containing a 200W element. The test tube and an Ellison GS4200 relative pressure gauge, in direct contact with the vapor, form a closed system. The heating rate is controlled using a 1 to 10 slider on the webpage interface. When set at 1 the element is heating 10% of the time and when at 10 is on 100% of the time. Careful control of heating is required to ensure stabilized temperatures and pressures within a reasonable time frame. The interactive platform is illustrated as a screenshot in Figure 2.

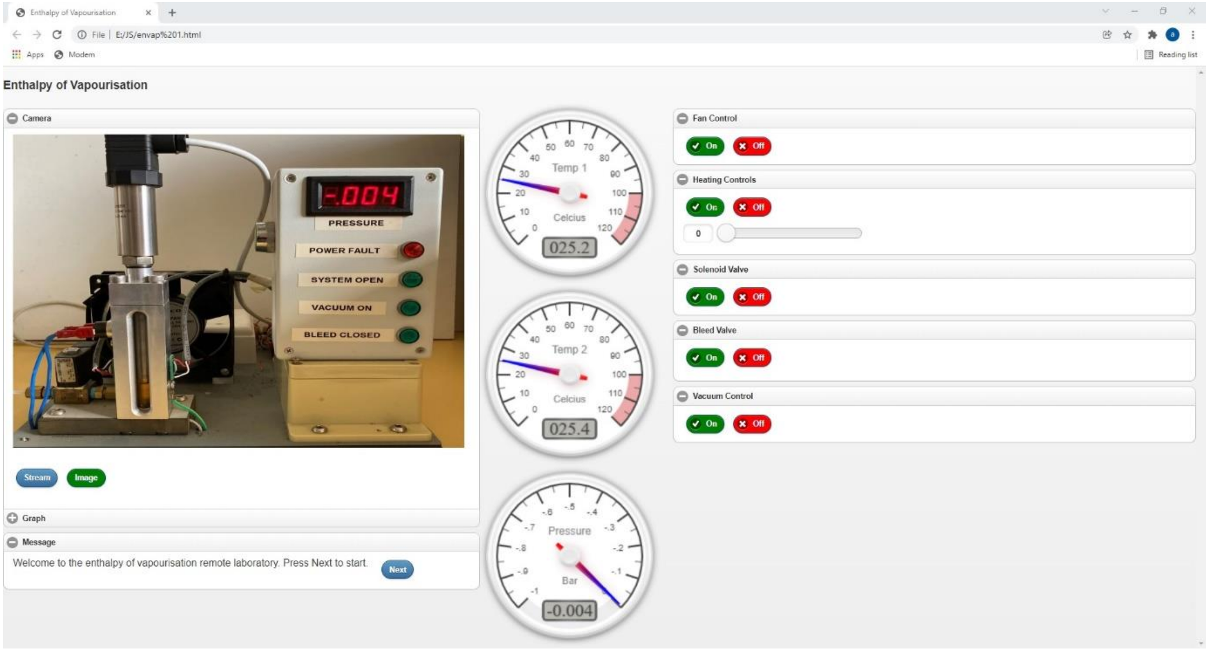


Figure 2. Screenshot of the webpage interface showing the controls available to the student.

Experimental Procedure

Typically, the process for the student conducting the remote laboratory is as follows. The website of the remote laboratory is opened, and the interactive platform illustrated in Figure 2 is shown to be available. After logging in with the user's specific account information, the apparatus located at UNE automatically begins to work, as depicted by the changing of the temperature scales on the right side of the screen. Initial instructions appear on the screen to guide the student's directions; a next-step instruction appears after the button *next* is clicked. The instructions are procedures to manipulate the equipment, including warnings on risks.

The first experimental step is to evacuate the air in the system by remotely accessing the vacuum pump. After closing the system to the pump and upon stabilization of the temperature both vapor pressure, *P*, and temperature, *T*, is recorded. The temperature of the system is then increased by a small increment using a remotely controlled slider. After stabilization of the pressure and temperature (typically 10 minutes), the values are recorded. Small increases in temperature and pressure, followed by recording the stabilized values are repeated multiple times up to a maximum of 100 °C.

For this experiment, the user is required to keep the temperature readings from the two sensors similar, indicating that equivalence has been achieved. The two temperatures and the measured pressure are then recorded. Users then increase the temperature slightly and again wait for equilibrium to be achieved before recording the new data. Students need to record at least five data points before commencing the data analysis. As this is a remote laboratory, unlike a traditional experiment, there is no need to set up the apparatus, wash glassware, or clean the table, etc. Therefore, the time for each session is relatively short, typically 60 minutes to set up the experiment and collect 5 data points.

METHOD

Survey Instrument Design and Validation to Measure Student Learning

As there were no existent instruments to assess interactions in the remote laboratory, a survey instrument was designed and developed. The criteria for the design were based on several resources: the literature review, the IULC instrument designed by our group,[25] and the laboratory observation sheet used in the face-to-face laboratories,[2] as well as the remote laboratory manual provided by UNE. Eventually, a preliminary version of the post-lab survey was designed and tested in a pilot study.

Pilot study

Three students, 2 in a group and one individual enrolled in the unit of *Chemical Energetics and Kinetics* at Curtin University, used the remote laboratory located in the chemistry department at UNE. This process was conducted to test the applicability of the items in the post-lab survey.

Improvement of the Instrument

After the pilot study, the design of the instrument was refined, and systematic procedures were conducted to improve the items. Three types of items were included in the post-lab surveys: namely Part A Student Interactions; Part B Student Opinions; and Part C Student Satisfaction about the remote laboratory. Please see the following for a detailed explanation.

***Part A* Student Interactions:** four types of student interactions were included in the study. The types of interactions were chosen based on Moore's work[26] for distance learning. Both remote laboratories and distance learning have the following similarities: a physical separation between the learner and other people/the apparatus; and an interface used to reduce this separation psychologically.[13, 19] From this aspect, the classification of interactions from Moore's work for distance learning were adjusted to be used for this study. In Moore's work, there were three types of interactions: Learner-Learner, Learner-Content, and Learner-Instructor. In this study, Student-Student interactions are equal to the Learner-Learner ones; Student-Internet and Student-Lab Manual interactions are equivalent to Learner-Content interactions, and Student-Instructor interactions resonate with the Learner-Instructor ones in Moore's classifications. The frequency of student interactions was measured by a 4-item scale, ranging from *never* to *many times*. The importance of student interactions was investigated by requiring the students to choose the five most important ones.

Part B **Student Opinions:** Two types of students' opinions about the remote laboratory were incorporated in the survey, namely the feeling of authenticity and flexibility. Authenticity and flexibility were chosen as they were two of the main significant beneficial characteristics that a remote laboratory conveys.[27, 28] When compared with other characteristics, like cost efficiency, which enables distance education, these two factors were more closely related to student opinions about a remote laboratory.

Part C **Student Satisfaction:** Student Satisfaction was measured by a 5-point Likert validated and reliable scale (*Strongly Disagree* to *Strongly Agree*) adapted from Arbaugh.[29] The internal reliability of the measure from Arbaugh (2000a) was validated by factor analysis as 0.92.[30] This scale focused on the measurement of student satisfaction with online courses, the students' perceptions of the quality of the course, and their intention of taking future courses at a distance. Even though the cohorts of the measurement were not completely the same as the ones in this study, there were similarities between them. All students were learning by distance and could not gain access to the materials physically. Besides, the design of Arbaugh (2000a) was presumed to assess the quality of the online courses which, from this aspect, were similar to this study.

The correlation between the three parts, the detailed information in each part, and the resources adapted are listed in Table 1.

Table 1. Interaction and Satisfaction Variables Included in the Post-lab Survey for the Remote Laboratory

Item Types	Item Names	Item Category	Sources
Part A Student Interactions	1. [a] Student-Student	1.1 Laboratory procedures/equipment	Modified from the classification of interactions form[26]
		1.2 Basic concepts	
		1.3 Analyzing data	
	2. Student-Internet	2.1 Lab procedures/equipment	
		2.2 Basic concepts	
		2.3 Analyzing data	
	3. Student-Lab Manual	3.1 Lab procedures/equipment	
		3.2 Basic concepts	
		3.3 Analyzing data	
	4. Student-Instructor	4.1 Ask the technician/instructor for help	
		4.2 Use the online help function	
Part B Student Opinions[b]	Authenticity	I felt I have done a real laboratory.	Adapted from[27, 28]
	Flexibility	The flexibility of doing a remote laboratory anytime anywhere is important to me.	
Part C Student Satisfaction	Immersion	I feel I was immersed in the laboratory process.	Modified based on the student survey [29]
	Ease of Use	I think the technology is easy to use.	
	Quality	The quality of this laboratory experiment compared favorably to my other face-to-face laboratory experiments.	
	Retry	If I had an opportunity to do another laboratory experiment via the Internet, I would gladly do so.	
	Overall Satisfaction	Overall, I'm very satisfied with this laboratory experience.	

[a]The numbers refer to the same sequence in the post-lab survey (Figure 3). [b]To makes it more convenient for the students to fill in the form, Part B and Part C were combined into Student Satisfaction in the post-lab survey.

The design of the actual post-lab survey used for this study (Figure 3) was as follows. Part A was divided into two parts: frequency and importance of interactions; Part B and Part C were combined into Student Satisfaction to reduce the students' mental load when filling in the survey.

Reflecting on the laboratory class you just completed:

1. How much have you talked with other students about ...	Never	Once	A few times	Many times
1.1 the procedures, protocols or lab equipment?	0	1	2	3
1.2 the basic science concepts behind the lab?	0	1	2	3
1.3 analysing your results?	0	1	2	3
2. Did you use online searching tools such as google about ...				
2.1 the procedures, protocols or lab equipment?	0	1	2	3
2.2 the basic science concepts behind the lab?	0	1	2	3
2.3 analysing your results?	0	1	2	3
3. Did you read the lab manual associated with this lab for ...				
3.1 the procedures, protocols or lab equipment?	0	1	2	3
3.2 the basic science concepts behind the lab?	0	1	2	3
3.3 analysing your results?	0	1	2	3
4. Did you...				
4.1 Ask the technician/instructor for help	0	1	2	3
4.2 Use the online help function	0	1	2	3

Please **choose ONLY 5 of those 11 items (from 1.1 to 4.2)** that you think are most important relating to the lab that you just finished and **rank them (#1 is the most important)..**

Rank	1	2	3	4	5
Item Name					
Example	*2.2*	*1.3*	*1.4*	*3.2*	*2.4*

(Student satisfaction) **Do you think…**	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
I felt I have done a real laboratory	1	2	3	4	5
The flexibility of doing a remote laboratory anytime anywhere is important to me	1	2	3	4	5
I feel I was totally immersed into the lab process	1	2	3	4	5
I think the technology is easy to use	1	2	3	4	5
The quality of this laboratory experiment compared favourably to my other face-to-face laboratory experiments	1	2	3	4	5
If I had an opportunity to do another laboratory experiment via the Internet, I would gladly do so	1	2	3	4	5
Overall I'm very satisfied with this laboratory experience.	1	2	3	4	5

Figure 3. The post-lab survey was used for the study.

Participants

There were two cohorts involved in this study. A Participant Consent Form was circulated before the conduction of the remote laboratory and illustrated that the project had been approved by the Human Research Ethics Committee of UNE and Curtin University. Students were also informed that the project would be carried out in line with the National Statement on Ethical Conduct in Human Research (2007). Also,-while completing the experiment was mandatory, this study was completely anonymous and voluntary. They could withdraw at any time. After the pilot study, all the second-year Chemistry students from UNE enrolled in the coursework unit *Physical Chemistry: Quantum and Thermal Structure,* and the students at Curtin University enrolled in the unit *Chemical Energetics and Kinetics* undertook the remote laboratory as a mandatory part of their courses. The students at UNE were manipulating the remote laboratory individually as they were mainly distance learners. While the students at Curtin University were required to undertake the laboratory in pairs as they were all on-site learners. Among the participants of Curtin University, three groups voluntarily completed the laboratory as a focus group. These students were interviewed immediately after finishing the laboratory activity. The other students who were not part of a focus group completed the remote laboratory more freely, choosing locations that suited them and without the researcher being present. To avoid a potential problem of more than one group choosing the same period, the available time sessions were circulated via *Doodle*,[31] an online time-scheduling website. In this platform, the students could see what sessions were available and the names of other students who had chosen the period. Considering that the students were from the same chemistry unit and had known each other for one and a half years, the *Doodle* link was not designed as anonymous. A maximum of two students was able to choose a one-time session.

Most of the students tried the remote laboratory more than once. 8 respondents out of the total 20 from UNE; and 39 from Curtin University out of the 75 in total, had completed the survey forms. For UNE, two students completed the remote laboratory once, 2 twice, and 4 completed more than twice. 4 of the students at UNE were on campus, and the other 4 were off campus. There was no definite relationship between the frequency of laboratory trials and the students' being on or off-campus. Both on-campus and off-campus students completed the laboratory once, twice, or more than twice. For Curtin University, as the log-in was scheduled based on the pre-determined timeline provided by the first researcher, the students only logged in once and no repeat log-ins were necessary. However, when the students were conducting the remote laboratory, all were required to finish two trials at the time session.

Data Collection

In this study, post-lab surveys, and interviews with focus groups were implemented to provide a multi-aspect description of the students' behaviors and experiences with the remote laboratory.

Surveys were used as the main data-collection strategies in all the remote laboratories. A post-lab survey after the completion of the remote laboratory activity was conducted. The survey was conducted via the online platform *Qualtrics*,[32] instead of the paper-and-pencil-based form because most students undertook the laboratory by themselves, not in the traditional classroom, and were not present in person. At the end of the laboratory, the focus groups of students were interviewed in person with questions based on their feedback to the post-lab survey to understand students' perceptions of the experience of remote laboratory manipulation.

Data Analysis

To provide a general picture of interactions that occurred in the remote laboratory in response to the first three research questions, figures were used to show (1) the frequency of Student Interactions in the post-lab survey; (2) the distribution of importance of Student Interactions in the post-lab survey; and (3) the distribution of Student Opinions and Student Satisfaction in the post-lab survey. To investigate the relationship between the strength of Student Interactions, Student Opinions, the Student Satisfaction variables, and the overall satisfaction item, Spearman's rank-order correlation coefficients were calculated using SPSS 25.0. To provide detailed information about the laboratory experience, the interviews from the focus groups were transcribed and analyzed.

RESULTS AND DISCUSSION

Frequency of Interactions - Results from the Post-lab Survey

Results from the post-lab survey were analyzed and are shown in Figure 4 in response to Research Question 1. After the completion of the laboratory, the students reported that they had interacted more frequently with the laboratory manual in all three aspects, namely, laboratory procedures, basic concepts, and analyze results. The students also responded that they had had more interactions with their peers about procedures than about concepts or results. For online help, the interactions arising from the analysis of results had the same frequency as those for procedures and concepts.

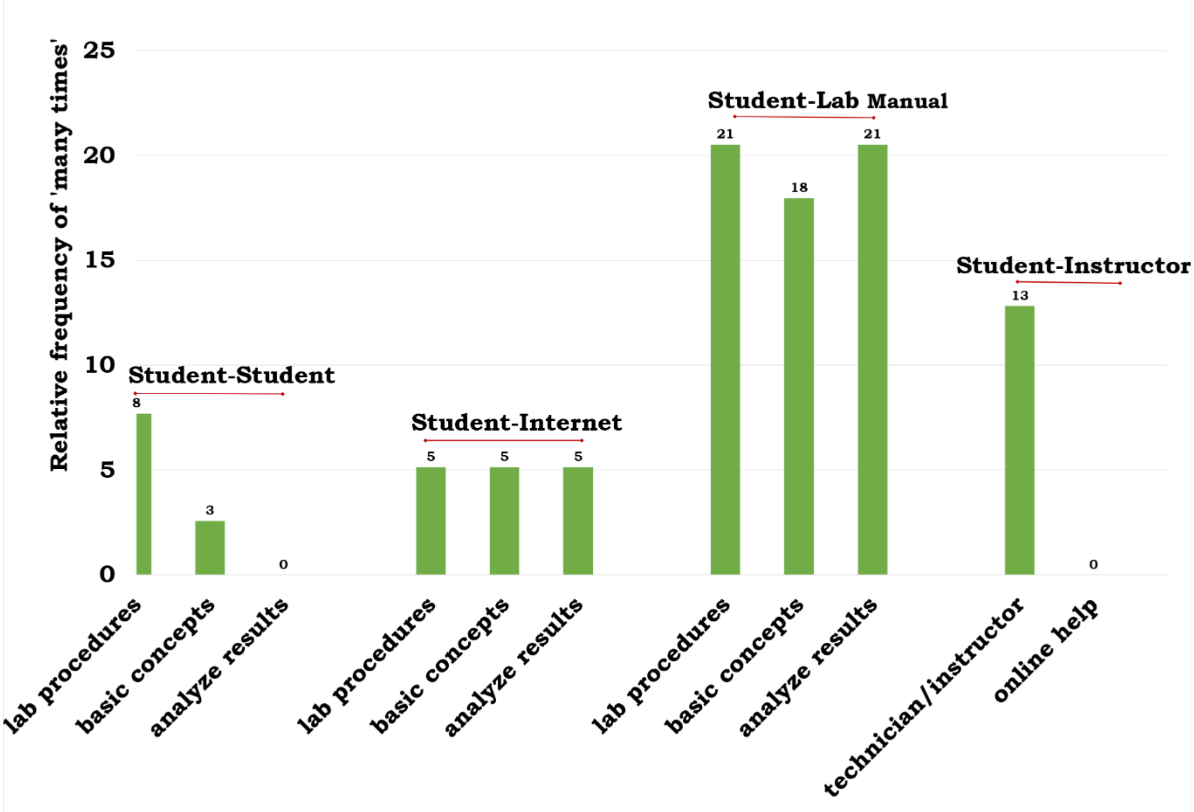


Figure 4. Relative percentage frequency of the interactions, sorted by task types, as reported to be *many times* by students after undertaking the remote laboratory work (N = 39). The percentage of each item is not equal to 100% as only data of *many times* are illustrated, not including data of *never*, *once,* and *a few times*.

Importance of Interactions - Results from the Post-lab Survey

The results of the post-lab survey were graphed as shown in Figure 5 in response to Research Question 2. The students reported that the top three types of interactions all refer to interactions with the laboratory manual, varying from procedures, concepts, and results. The fourth most important interaction was to discuss results with their peers and to ask for help from the technician/instructor. It is, therefore, necessary to point out the indispensable role of the laboratory manual when the students are working in a remote laboratory. In the process of conducting the laboratories, the instructors from whom the students were accustomed to requesting information in face-to-face laboratories were either physically absent or were not conveniently available. The laboratory manual is the most directly related source for the specific laboratory.

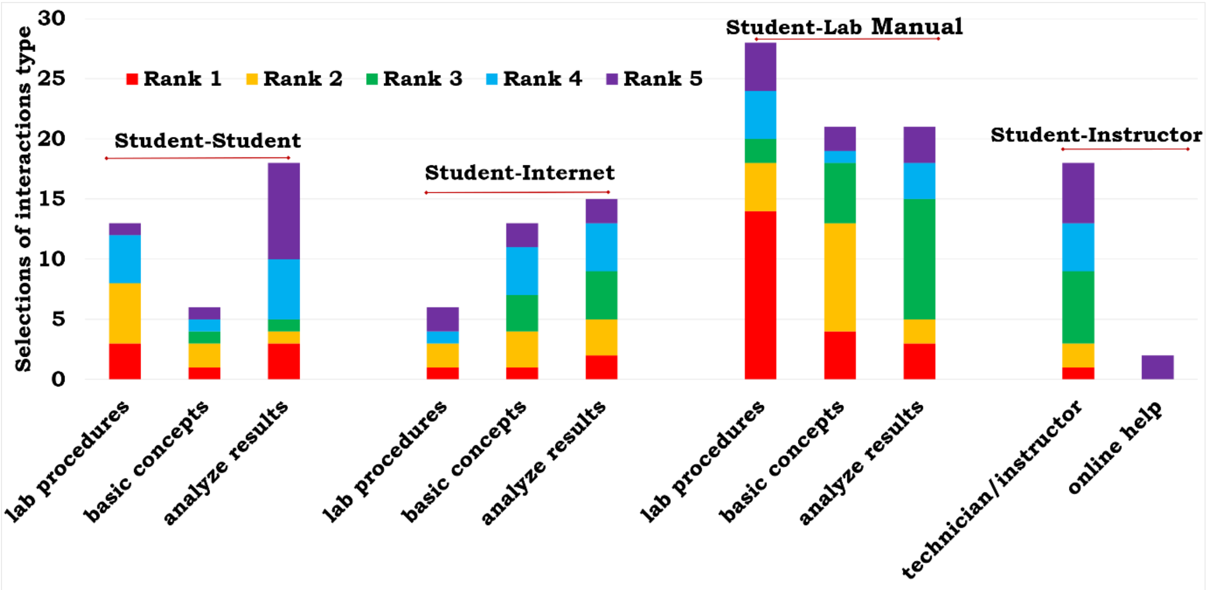


Figure 5. the raw number of importance of the interactions, sorted by task types, reported by students of UNE and Curtin University after undertaking the remote laboratory work (*N* = 32).

Student Satisfaction

The overall experience using the remote laboratory, in response to Research Question 3, was collected in two ways, namely the post-lab surveys (all students) and the interviews (focus groups). The items about Student Opinions, Student Satisfaction variables, and the Overall Satisfaction item (Figure 6) were included in the post-lab survey.

The subscale of Student Opinions, Student Satisfaction variables, and the overall satisfaction item consisted of seven items and the internal consistency was $\alpha = 0.85$, meaning the variables were reliable.[33] Overall, the students exhibited satisfaction with the remote laboratory, although not all students believed that they had performed an authentic laboratory (43.6% chose *strongly disagree* or *disagree*, calculated from data in A, Figure 6). They did not feel immersed in the process and reported that the quality of the laboratory was not very high compared with the face-to-face laboratories. On the positive side, the characteristics of the flexibility and easy-to-manipulate apparatus may have led to their preference to carry out another remote laboratory and their overall positive satisfaction.

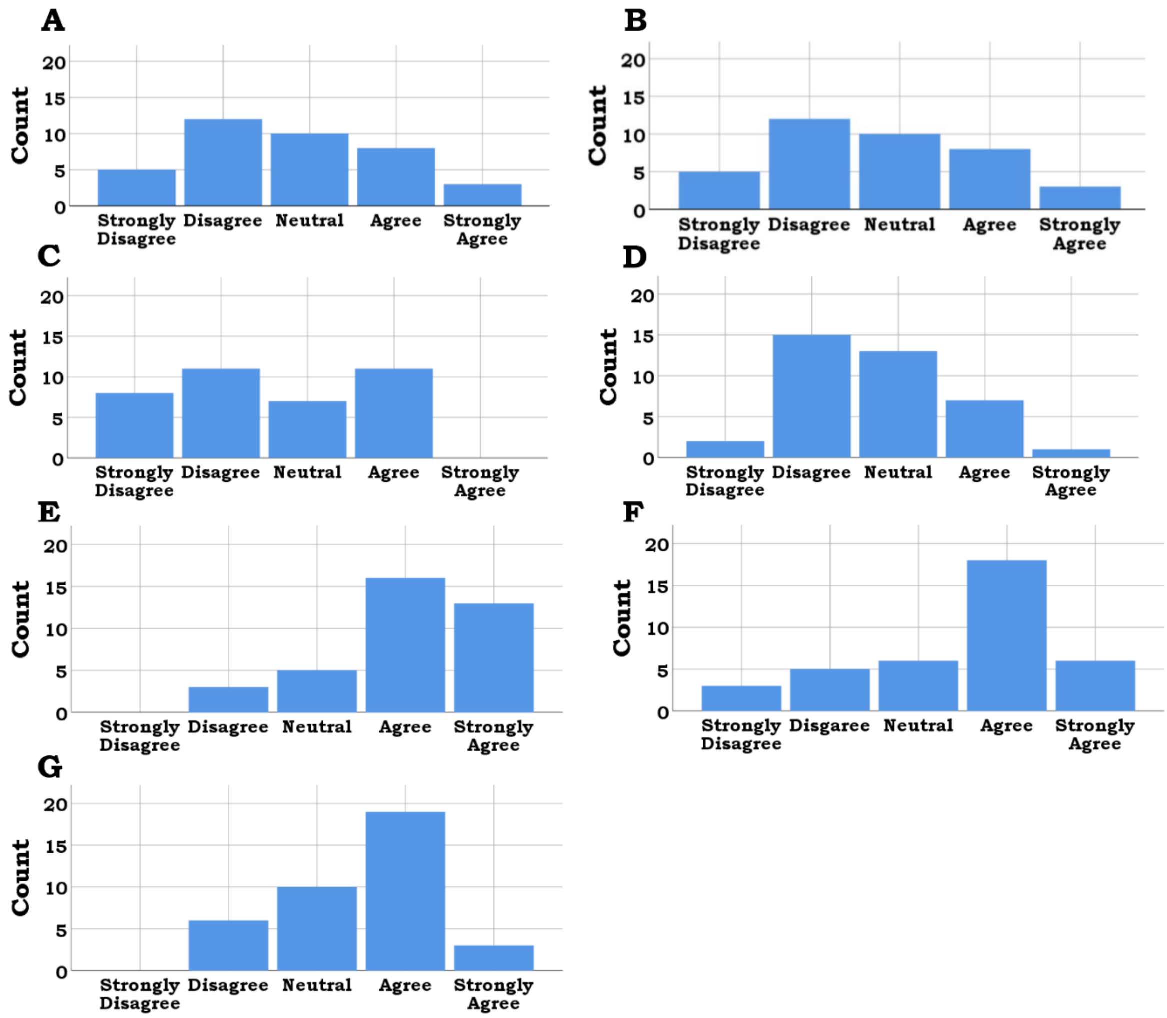


Figure 6. the raw number of selections of student opinions obtained from Part B and Part C, post-lab survey. (A) Authenticity; (B) Flexibility; (C) Immersion; (D) Ease of Use; (E) Quality; (F) Retry; and (G) Overall Satisfaction (N = 39).

Student Interviews

Further interviews were carried out with three groups. In group 1, the students expressed a preference to work with instructors present because *the lab demonstrator can correct their problem before making mistakes*. They did not mind conducting another remote laboratory if *it's explained better, and the step-by-step [is made] clearer*. In group 2, one of the students also stated that he was familiar with the remote laboratory experience because it was like some laboratories in engineering. Generally, the two students reported that the laboratory was not hard, however, it was a boring experience because *the waiting time was far too long*. However, they affirmed that they would rather *…wait longer to get the proper values*. In the remote laboratory, there was no clear guidance about the expected waiting time. This uncertainty lowered the learning experience for the students who believed that if this was initially identified, they would not think that the long waiting time was a negative factor.

The third group of two students interviewed presented more detailed information about the laboratory itself. Overall, they preferred to conduct the laboratory with an instructor present instead of finishing it at home. One student mentioned that he would probably have failed because he would not have figured out what to do. Both students were concerned with making mistakes even though in the remote laboratory they were provided with the opportunity to attempt the experiment several times and they could learn from their mistakes. For the equipment, they thought the guidance about the two temperature bars was not clearly labeled, and they did not realize they needed to stop heating, before waiting for the completion of equilibrium. The students did not like smelly odors and the necessity to clean up that was present in the face-to-face laboratories, so this was a benefit of the remote laboratory. And, they would like to have another attempt for one more remote laboratory because they believed that doing laboratories online was reasonable, *it's still interactive, and we did learn something during the process*. However, they insisted that the guidance should be planned carefully, especially for the learners who were manipulating the equipment by themselves. They acknowledged the positive side of the flexibility of a remote laboratory. One student preferred to work in a group, with peers, if it was possible.

Interaction Types and Satisfaction

Statistical analyses were made between the 18 Item Categories (the second column in Table 1) and the last item ((overall satisfaction) in Part C of the post-lab survey), in response to Research Question 4. Results from Spearman's rank-order correlation coefficients (Table 2) illustrated that among the interaction types, only the interactions with the technician (within the Student-Instructor type) were reported to be significantly related to the overall satisfaction levels. Furthermore, among the other features of satisfaction, the quality of the remote laboratory, the preference of trying another remote laboratory, the easy-to-use equipment, the feeling of immersion during the laboratory process, and feeling of having done a real laboratory all showed a significant positive correlation with the overall satisfaction. However, flexibility did not have significant strength with overall satisfaction as explained below.

Table 2. Spearman's Rank-Order Correlation Coefficient for the Frequency of Interactions, Student Opinions, and Other Satisfaction Variables with Overall Satisfaction[a]

Interaction Type	Opinion	Satisfaction				Number of Participants
Student-Instructor	Authenticity	Immersion	Ease of Use	Quality	Retry	N
.457[b]	.397[c]	.469[b]	.588[b]	.652[b]	.675[b]	39

[a]Only significant values are shown. [b]Effects are significant at the 0.010 level. [c]Effects are significant at the 0.050 level

To sum up, based on the students' reports, the more interactions with instructors (in this case technicians), the more they were satisfied with the laboratory. The frequency of other interaction types, namely Student-Student, Student-Lab Manual, Student-Internet, did not show significant correlations with the overall satisfaction level. In addition, the more the students felt that they had done a real laboratory, the more they felt immersed in the laboratory activity, the easier to use the equipment, the higher quality of the remote laboratory, and the higher willingness to try another remote laboratory, all significantly related to the higher level of satisfaction with the remote laboratory activity. By contrast, the flexibility of the remote laboratory did not correlate with the overall satisfaction level. Unlike students at UNE, the students at Curtin University who participated in the remote laboratory could not choose any time that suited them but conducted the remote laboratory based on the pre-designed time schedules through *Doodle*. This decrease in flexibility might have caused a lack of correlation between flexibility and satisfaction. Nevertheless, from the interview, the students showed that the flexibility of a remote laboratory might be beneficial for some students.

CONCLUSIONS

In this article, a remote experiment to measure the enthalpy and entropy of vaporization of *n*-octane was presented. The remote experiment, initially designed for distance learners in one university, also was completed by a much larger group of students from another university who were enrolled as face-to-face students (although they were doing the remote laboratory by distance). None of the students complained about any technical problems, such as lag of speed. In contrast, most students were satisfied with the quality of the remote laboratory. It was presumed then that this remote laboratory would satisfy more audiences and could provide more learning opportunities from various institutions, just like the cohorts in the study had experienced.

However, it is not enough to consider only the quality of the laboratory itself when assessing the learning effects of a remote laboratory. Like traditional laboratory learning, the learning goals, for example, technical skills, conceptual development, student attitudes to chemistry/science, attention to laboratory safety, etc., should and could be taken into account. For this remote laboratory, skills about concept development and abilities of data analysis were integrated into the laboratory manual. This aligned well with most of the learning goals of remote laboratories.[34] Besides, the consciousness of laboratory safety could be attained in a much safer way in this experiment. The laboratory would be restarted if overheated; one group of students had experienced this when the laboratory was reset and the temperature was too high. Even though students could exceed the stated safety limits of the experiment, doing so taught the students a lesson, compared to the potential consequences of such risks are taken in face-to-face laboratories. There were few technical skills required or learned with this remote laboratory. For example, there were no activities using traditional laboratory glassware. However, some skills could be developed, such as controlling equipment via the Internet and the computer, such as changing the temperature meticulously to achieve equilibrium. This experience of interacting with equipment through technology is good preparation for the future workforce.

In addition, we described and analyzed the frequency and importance of a range of types of interactions in which undergraduate students were engaged during this remote laboratory experiment. The following discussion provides more details.

Frequency and Importance of Interactions

The frequency and the importance of interactions were compared between the three Student-Student items and the two Student-Instructor items in Figures 4 and 5. In the remote laboratory, the laboratory manual was both frequently used and was regarded as important by the students, for referring to procedures, trying to find some concepts, and analyzing results. By contrast, even though Student-Student talking about procedures happened frequently, discussing the results was considered more important.

Even though asking for help from instructors was not so frequent, the students thought that this type of interaction was important. From the interview results, some students in Curtin University stated that they would prefer to have an instructor present. Some of the students in the focus groups stated that the instructors could help them to check their process and ensure the validity of the procedures, while others were afraid that they might not finish the laboratory if no guidance with some procedures was provided. This result aligned well with previous findings of the importance of asynchronous human instructors in addressing some problems.[35] The first focus group, on the contrary, showed themselves to be more confident and believed that they could complete the laboratory without a physically present instructor. When asked whether they could implement the remote laboratory without laboratory pairs, they were self-assured that individual work was not a problem. These comments suggest that at least part of the roles of an instructor could be supplemented by the meticulous design of remote laboratories, mostly in the form of Student-Lab Manual interactions.[36] These comments are also supported by another of our findings: All the students believed that clear guidance and goal setting were indispensable components in the remote laboratory progress.

Interactions in the Remote Laboratory and Students' Satisfaction

In the remote laboratory, the interactions between the students and the instructor were far fewer because most of the students completed the experimental task without an instructor present. There were no indirect interactions because the students were doing a remote laboratory without other groups. It may be assumed that these limited types of interactions might impact learning experiences, but the results did not fully support this assumption. From the interviews, having no instructor present meant that the lack of Student-Instructor interactions created confusion for some students. However, the students also believed that they could complete the task without an instructor if there was guidance in the laboratory manual and that the platform was clear enough. This idea can also be affirmed by a study made by Böhne et al,[37] in which the instructor was considered more as a tutor in solving technical problems by the students manipulating the remote laboratories than as a facilitator of learning. The students in this research study were satisfied with the remote laboratory generally. Complaints were more about the confusion caused by a procedure or one unit conversion during the calculation process than about the technology itself. The students acknowledged that remote laboratories were interactive and that the equipment was not hard to manipulate. Also, the easy-to-use equipment had positively affected the students' overall satisfaction with this remote laboratory. Students tended to look to the laboratory manual when they had problems. Even though there was not a positive correlation between the frequency of Student-Lab Manual Interactions, the lab manual was reported to be important for learning. Therefore, a well-designed laboratory manual with clear guidance can increase the students' learning experiences using a remote laboratory and can supplement part of the change in the type of interactions. Even though no specific studies about remote laboratories were found to be relevant to the design of laboratory manuals, the findings from one study might provide some hints for remote laboratory developers.[38] In this study, an electronic laboratory manual/notebook was introduced and analyzed and the students interacted with the laboratory manual mainly by accessing *Google Doc*s. This type of Internet/technology-integrated laboratory manual was reported to have many advantages. As the Internet and technology is also an indispensable part of the process of remote laboratory learning, it seems to be applicable to develop the laboratory manual and technology to a greater extent.

Implications for Teaching and Learning

The remote laboratory introduced in this article provided students with the opportunity to explore fundamental chemical thermodynamic concepts from observations and analysis of data from an actual experiment. As attendance at a face-to-face laboratory is not required, the experiment can be repeated many times and at the time of the students choosing. The safe running of the experiment is automated, with online instructions and training. There are also benefits in providing access to laboratory learning for students in remote locations, during travel restrictions, and can be shared with multiple universities. The successful integration of this remote laboratory in the curriculum at two Australian

Universities has demonstrated that it can be an important and effective supplement for face-to-face laboratories.

While the interactions explored in this study focused on one remote laboratory, this analysis of students' interactions could be extended to a broader range of remote laboratories. This research was a first step in constructing an instrument that combined research studies of distance education and technology-supported learning processes. This attempt provides new prospects when investigating human-computer interactions, especially the studies of these interactions during practical work.

LIMITATIONS

There were several limitations to this research.

Design of the instruments

In the data collection instruments used in this study, only several items relating to interactions were included. However, the learning environment is complex and other factors such as gestures, mechanical devices, etc. also may have played significant roles in the learning process.[39] However, it is difficult to include all the factors in one study, and the focus of this study was only on the impact of measurable interactions based on the selected types of interactions that were involved.

A limited number of UNE participants in the remote laboratory

Only a small number of UNE students were involved in the analysis, so it is hard to generalize these findings to other students learning distantly when using remote laboratories. Nonetheless, eight students out of twenty students had completed the survey. One possible advantage of this circumstance was that the students represented a variety of characteristics of the participants of the students doing remote laboratories individually.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.]

the Smartlab Laboratory Manual and an Example of Raw Data and a 'good' Graph (DOCX)

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Notes

The authors declare no competing financial interest.

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