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Analysing student written solutions to investigate if problem-solving processes are evident throughout

Regina Kelly[a], Eilish McLoughlin[a] and Odilla E. Finlayson[b]

[a]CASTeL, School of Physical Sciences, Dublin City University, Dublin, Ireland; [b]CASTeL, School of Chemical Sciences, Dublin City University, Dublin, Ireland

ABSTRACT

An interdisciplinary science course has been implemented at a university with the intention of providing students the opportunity to develop a range of key skills in relation to: real-world connections of science, problem-solving, information and communications technology use and team while linking subject knowledge in each of the science disciplines. One of the problems used in this interdisciplinary course has been selected to evaluate if it affords students the opportunity to explicitly display problem-solving processes. While the benefits of implementing problem-based learning have been well reported, far less research has been devoted to methods of assessing student problem-solving solutions. A problem-solving theoretical framework was used as a tool to assess student written solutions to indicate if problem-solving processes were present. In two academic years, student problem-solving processes were satisfactory for exploring and understanding, representing and formulating, and planning and executing, indicating that student collaboration on problems is a good initiator of developing these processes. In both academic years, students displayed poor monitoring and reflecting (MR) processes at the intermediate level. A key impact of evaluating student work in this way is that it facilitated meaningful feedback about the students' problem-solving process rather than solely assessing the correctness of problem solutions.

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The Organisation for Economic Cooperation and Development (OECD) (2013) reports that everyday workers are challenged with new complex problems that require them to apply their knowledge and devise methods that will allow them to solve problems. Workers are required to tackle problems that are not entirely discipline specific and the method to solve may be somewhat unfamiliar. This evolution from workers completing routine procedures has required education institutions to respond to the demands of the work force. Students need to be equipped 'with highly codified, routine skills to empower them to confront and overcome complex, non-routine cognitive challenges' (OECD, 2012, p. 26). Previous research carried out at Dublin City University recommends that third-level instructors should aim to create undergraduate science curriculum that

CONTACT Eilish McLoughlin eillish.mcloughlin@dcu.ie

facilitates students developing skills and knowledge that is relevant to a future science career and is active rather than passive learning (Lovatt & Finlayson, 2013).

Different types of problems require students to use different processes. Some problems contain all the information needed to solve, a specified goal and recognised limited methods to solve, these problems are defined as well-structured problems (Jonassen, 2000). Alternately, ill-structured (Simon, 1977) or ill-defined problems (Mayer & Wittrock, 2006) may be missing information, have undefined goals, no specific method, have several solutions, may require the solver to put forward an opinion, and require justification of associated assumptions. The overreliance on well-structured problems causes students to be underexposed of recognising, representing, and justifying problems (Mayer & Wittrock, 2006; Pretz, Naples, & Sternberg, 2003), which limits the students' development of these skills.

Providing evidence of competent problem-solving

When an instructor grades a problem are they identifying what is adequate/inadequate about the students problem-solving or are they focused on a correct solution? Henderson, Yerushalmi, Kuo, Heller, and Heller conducted research in relation to the challenge educators face in consistently grading student solutions due to the 'conflict between instructors' stated goals and grading practices' (2004, p. 164). They identified that educators feel required to reduce student marks only when there is evidence that incorrect science or methods are used, this they termed the 'burden of proof'. They suggest that the 'burden of proof' should be transferred to the students, as they should feel required to display their reasoning.

When students are instructed to explicitly justify their reasoning when solving a problem, can student solutions provide educators with enough evidence to analyse student problem-solving processes? This research was carried out on the premise that student solutions can infer the processes required to solve a problem when present. Currently, there is no definitive method to assess student solutions that is valid, reliable, and practical (Docktor & Heller, 2009b). Taraban, Craig, and Anderson (2011) state that student written solutions comprise more information than is typically obtained from grading. Docktor and Heller (2009a) conducted research to compare students' written solution and students' oral explanation of a solution and analysed both with a grading rubric, they concluded that student written solutions present an authentic interpretation of student problem-solving processes. Grading rubrics have gained popularity as a means of assessing student solutions to provide formative assessment to students. Panadero and Jonsson (2013, p. 129) define grading rubrics as 'documents that articulate the expectations for an assignment, or a set of assignments, by listing the assessment criteria and by describing levels of quality in relation to each of these criteria'. Rubrics have been advocated on the basis that they increase student transparency of educator expectations (Andrade & Du, 2005), lessen student anxiety in relation to coursework (Kuhl, 2000), support student feedback (Schamber & Mahoney, 2006), and develop student self-efficacy (Andrade, Du, & Wang, 2008). However, rubrics can be limiting, the 'one size fits all problems' can be confining in acknowledging particular aspects of problem-solving process relevant to a problem (Hull, Kuo, Gupta, & Elby, 2013).

Kim and Tan (2013) recommend that in order to promote collaboration on a problem, student interdependence should be considered. Regarding the difficulty of a collaborative problem, Vygotsky (1978) recommends it should be more difficult than an individual problem as it requires students to collaborate. Pivotal research conducted by Vygotsky (1978) describes the learning progression of students when solving a difficult problem collaboratively with a 'more capable' peer. He terms the Zone of Proximal Development as the distance between the current level of development by an individual learner and the potential development by the collaborative learner. It is proposed that after collaborating on a problem, a student's Zone of Proximal Development has been elevated (Shabani, Khatib & Ebadi, 2010). Peer interaction can act as a scaffold for students when problem-solving as students share explanations, build mental models, and debate ideas (Ge & Land, 2004; Hake, 1998; Wieman & Perkins, 2005). Kim and Tan (2013) also note that group dynamics may vary students' collaborative experience and impact students' views, behaviours, and learning outcomes. The impact that variables in group composition have on the learning outcomes of collaboration is complicated and can be very difficult to build coherent associations between variables (Dillenbourg, Baker, Blaye, & O'Malley, 1995).

Purpose of the study

Traditional assessment of student course work generally assesses student accuracy relating to the knowledge content. This, however, does not provide evidence of student problem-solving processes. The purpose of this study is to assess if a devised problem used in an interdisciplinary science module achieved the intention of developing student problem-solving skills. A problem was created by a team (undergraduate students, postgraduate students, and science, technology, engineering, and mathematics education researchers) at Dublin City University, with the aim of requiring students to use problem-solving processes to devise a logical solution. Students were instructed to provide clear statements of their assumptions and choice of calculations in their written solution. Student solutions from two academic years were analysed to investigate if students' problem-solving processes were present/absent. The specific research questions being investigated are:

1. What methods do student use to solve an ill-structured interdisciplinary science problem?
2. What problem-solving processes are present or absent in student written solutions?
3. How does peer interaction impact student problem-solving skills?

A framework for analysing student solutions

Our analytical framework used the problem-solving framework presented by the OECD Programme for International Student Assessment (PISA) to research individual computer-based assessments of problem-solving competencies (OECD, 2012). There are some similarities between the different strategies put forward by cognitive psychologists in relation to problem-solving (Gok, 2010; Polya, 1945; Reif, 1995). The PISA problem-solving framework (OECD, 2012) is grounded upon research conducted by Mayer and

Wittrock (2006), Bransford, Brown, and Cockling (1999), Reif (1995), and Polya (1945). The framework categorises the processes associated with problem-solving as, exploring and understanding (EU), representing and formulating (RF), planning and executing (PE), and monitoring and reflecting (MR). At the top of the framework is the EU processes, which is associated with the exploring of a problem to acquire information that allow students to understand the issue (OECD, 2012). It may also involve understanding the relevant information in a problem. RF in a problem includes choosing important information and combining it with prior knowledge structures to construct a meaningful mental image of the problem (OECD, 2012). PE involves using the problem information and selected scientific principles to construct a procedure to obtain a solution and to carry it out. MR involves checking midway and final outcomes, evaluating the suitability of assumptions used and reflecting on alternative views (OECD, 2012).

Much research has been conducted by cognitive psychologists in the area of problem-solving processes; the assessment of problem-solving processes is where the challenge lies (OECD, 2012). In this research, it was intended that students would display their cognitive problem-solving process in their solutions. This framework was used for collaborative rather than individual problem-solving as research conducted by Heller, Keith, and Anderson (1992) concluded that enhanced problem solutions were developed though collaborative rather than individual practices. It was also stated that collaborative problem-solving enhanced the achievements of students, regardless of their capabilities. Collaboration facilitates students sharing their understanding of the problem, relevant conceptual knowledge, procedural knowledge and aims to promote students monitoring their selection of assumptions and methods by asking group members for clarification. The complex cognitive structures of the students were not the focus of this research. The motivation of this research was to investigate if relevant problem-solving processes were evident in solutions when students had been instructed to devise a solution that justified their reasoning throughout. The solutions would then be used as evidence to confirm if problem-solving process were present. This evidence could infer that a problem-solving process was present. It is important to note that the authors did not assume that a cognitive process was absent from a students' mental processing if it was not evident in their written solution. Having evidence of problem-solving processes in written solutions is favourable as it provides feedback to educators of large-scale third-level classes. Mayer and Wittrock (2006) argue that students' problem-solving skills can be analysed by its component process. The use of this framework can allow tutors to give consistent feedback to students regarding their problem-solving processes rather than feedback in relation to the content matter of the problem (Figure 1) .

The study

Participants in the study were students enrolled in a first-year 'Interdisciplinary Science' module; 181 students were enrolled in the module in 2014/2015 and 192 in 2013/2014. The range of courses enrolled in the 12-week module was Bachelor of Science degree programmes in Analytical Science, Biotechnology, Chemical and Pharmaceutical Science, Environmental Science and Genetics and Cell Biology. The interdisciplinary science course intended to provide students with the opportunity to develop a variety of skills (Table 1) in relation to: real-world connections of science, problem-solving, information

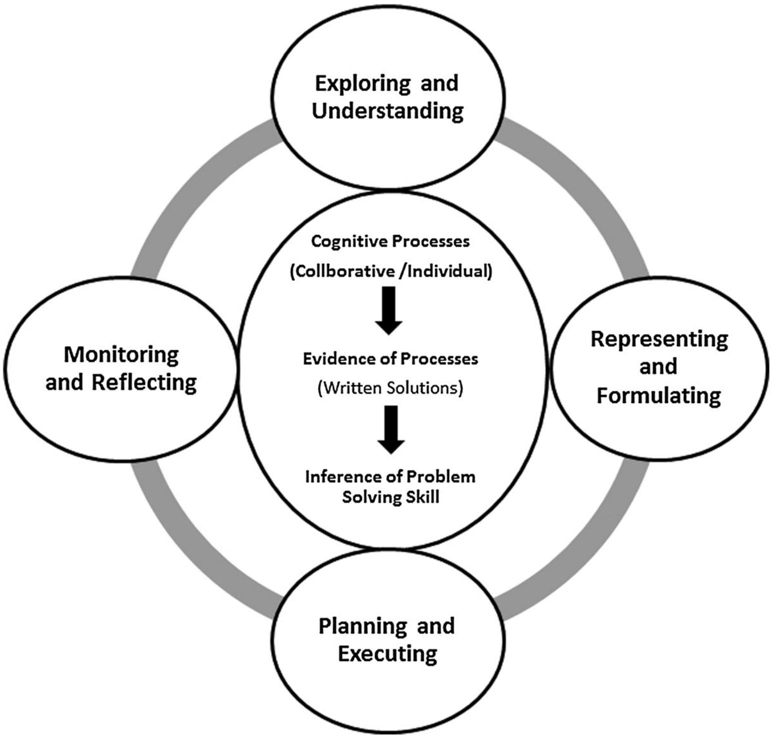

Figure 1. Framework used to analyse student written solutions.

and communications technology (ICT) use, team work, and oral communication while linking subject knowledge in each of the science disciplines (McLoughlin & Finlayson, 2014).

Participants worked in groups (interdisciplinary) over the semester, these groups remained fixed for the duration of the module. Students enrolled in the module were allotted three hours of instruction per week. This time was divided to include a one-hour lecture and a two-hour group work session. Students were allocated an assignment in their lecture, researched outside of class time, and then completed the assignment collaboratively in their class time. Students submitted various formats of assignments once a week, for example, research posters, speeches, and poster. This research focused exclusively on the second topic in the module, Cow Problem (Table 1).

The Cow Problem

The Cow Problem was assigned in the second week of the 'Interdisciplinary Science' module and students were given one week to solve. It was proposed that an ill-structured problem would challenge the students and require them to use all problem-solving processes (EU, RF, PE, and MR processes). The problem method was goal assigned but left completely open so that various solutions were possible and students were required to make and justify assumptions. The problem was related to a real-world scenario and integrated science disciplines rather than being subject specific. The students were facilitated

Table 1. Overview of interdisciplinary science module (McLoughlin, Finlayson, & Kelly, 2015).

Skill/key objective	Title of problem	Brief overview of instruction
Introduction to group work, think of relevance of science	Everyday Science	Choose only one of the following: an industry; a product that you use frequently; an Irish product. Research and prepare a poster to describe in detail the scientific process involved or the science behind the product
Collaborative problem-solving processes	Cow Problem	From a picture of a cow with a backpack used for collecting gaseous emissions, determine whether a cow herd could be used to produce all the power required in the average family home
Modelling, teamwork	Home Brewing	Given an outline of the brewing process and specific details on vessels used, conduct energy and thermodynamic calculations to decide on an appropriate selling price per litre of beer. Prepare a business plan of the model used
Defending ethical and scientific arguments, oral communication	Genetic Screening	Presented with family tree and seven perspectives on Friedreich's ataxia and pre-implantation genetic diagnosis (PGD), prepare and contribute to a debate defending the views of a particular perspective on PGD
Link real-world issues, interpreting	Oil Spill	Provided with details of an oil spill and a deployed boom to contain the oil in the sea. Students are asked to perform various calculations about amount of oil that has escaped, titration and discuss oil spill clean-up methods
Data mining, analysis and representation	Oodles of Data	Provided with research data from a multi-parameter sonde (sensor) in Dublin Bay, which collects data every 15 minutes over the period of a month, depict the data graphically to aid interpretation
Creative application of science, relevance of science	Own Problem	Choose an application of science (a context) that your group is interested in. Discuss the context and identify aspects of physics, chemistry and biology (the concepts) that are relevant to the application. With this knowledge, develop a problem suitable for use in module

in collaborating in groups during class time, tutors were asked to refrain from directing solutions or strategies. The problem was created with the objective that it built on current knowledge of first-year undergraduate science students who had covered the basics of biology, chemistry, and physics in the previous semester. Students were given the freedom to choose any method they deemed suitable to solve this problem; therefore, numerous potential solutions could be possible depending on their interpretation and assumption.

Coding system

Content analysis of the solutions was performed to provide insight into how the students solved the problem and the evidence they provided to display their reasoning. This approach was selected as it is a reduction technique that enables researchers to examine trends in documents and make inferences from these trends (Stemler, 2001). First-level coding was performed on student solutions using descriptive codes (Punch, 2009). Descriptive coding was performed to describe the information selected/used, theories chosen, methods chosen, and conclusion drawn. Topic coding was performed where the authors labelled sections of solutions according to its relevance. Solutions were analysed regarding the steps taken to solve the problem and particular parts of the solution were labelled, for example, assumed volume, calculated number of moles. In general, student solutions followed one of two main methods when solving the problem. The steps of each of these methods were labelled and second-level coding was performed to infer whether the four problem-solving processes were evident. Specific criteria that would indicate whether a particular step displayed a problem-solving process were then discussed within the research team. For example, if assuming a value, this value must be justified to provide a relevant argument. If there is no justification, this does not display monitoring and reflection process. Problem-solving processes were then mapped onto the solutions and Tables 2 and 3 were drafted. Finally, analytic coding was used to infer whether a particular problem-solving process was evident or not in student solutions. The coding was reviewed by research team members individually and then compared (Punch, 2009). Particular attention was given in instances where researchers had alternative interpretations regarding the relevance of problem-solving processes for each particular solution step. Tables 2 and 3 were finalised after the research team reached a final conclusion. To make valid inferences from the solutions, several members of the research team coded the same text in the same way (Weber, 1990).

Problem-solving processes evident in solutions

Maloney (2011, p. 3) advises that problem-solving encompasses 'a very diverse and complex set of processes'. The first part of the problem was as follows: 'You are given pictures of the cow back – pack for collecting gaseous emissions from the cow. Estimate the amount of gas that has been produced by the cow in one day, assuming that the pack is filled' (Figure 2).

From the analysis of the solutions, two distinct methods were identified. The first method was to find the amount of gas by estimating the dimensions of the cow back pack in some way, then calculate the volume of it. The second method was based on students' assumptions, students assumed a value for the amount of gas produced by a cow. An analysis of the solutions revealed the steps taken by students in each method (Table 2). Problem-solving processes were then assigned to the steps of the problem by the researchers (Table 2).

The second part of the question stated 'Assuming that the majority of this gas is methane (CH_4), discuss, with figures as appropriate, whether a cow herd could be used to produce all power required in the average family home' (Table 3). In general, student solutions contained three main parts: the first was that a value of the energy

Table 2. Estimate the amount of gas that has been produced by the cow with problem-solving process.

Method One	Problem-solving process
Identify that the backpack is a cylinder shape	EU
The dimensions of the cylinder are comparable to the size of the cow and/or man in the pictures	EU
If assuming any information, reference must be given	MR
Identify formula to find volume of a cylinder	RF
Correctly apply *h*, *r* values	PE
Method Two	Problem-solving process
Assume a value for the volume of gas	EU
Evaluate assumption critically by comparing to a referenced source	MR

Notes: Method One is the step taken to find volume of backpack through calculation. Method Two is the step taken to find volume of backpack through assumption.

Table 3. Investigate if a cow herd could be used to produce all power for a family home with problem-solving processes.

Energy required to power home	Problem-solving process
Assume energy needed for a family home	EU
Evaluate assumption critically by comparing to a referenced source	MR
Energy produced by cows	Problem-solving process
Prior information: combustion of methane formula *or* another logical method from a researched source	RF
Must devise a strategy to find how much energy is in gas	PE
Must execute this strategy correctly	PE
Conclusion	Problem-solving process
Compare the energy needed to the energy supplied	MR

used in the average family home needed to be assumed. It was necessary that this value was cross-checked with a referenced source to justify the suitability of its use. Secondly, the amount of energy obtained from a particular quantity of gas needed to be calculated. All students had completed a module in the previous semester that explained the combustion of the methane formula. This principle may have been used to calculate how much energy may be derived from an amount of gas (moles or mass). To complete this calculation, the students would have needed to state the combustion of the methane value for either mass or moles, and then calculate how many moles or how much gas was in a specific volume of gas, then, multiple this number by the combustion of methane value. If a student used another method apart from the combustion of the methane formula, for example, an assumed relationship between the amount of gas and the energy that could be derived from it, they needed to logically justify their choice of method.

Finally, the students needed to formulate a conclusion about whether it would be possible for a cow/s to produce enough power required for the family home. In order for their conclusion to be valid, they had to compare the value of energy produced by the cow to the value of energy required by the home.

Student views

To gather qualitative data about the students' experience when solving the problem, a survey question was administered ($N = 95$) after the students completed the problem. It included a multiple-choice closed question with a space for students to discuss their

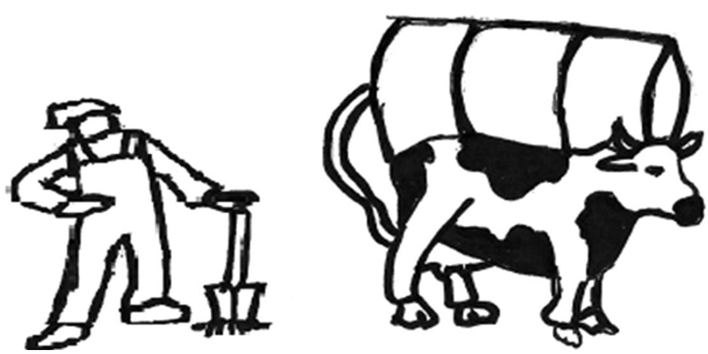

Figure 2. Sketch of Cow Problem.

answer. The findings from this question prompted the need for focus group discussions in relation to the amount of collaboration that occurred during student construction of a solution.

Focus group discussions were also conducted to gather data about students' perceptions of solving a problem collaboratively. Seven focus group discussions facilitated a total of 26 participants after the sixth week of the module. Students were facilitated in talking freely and spontaneously about their experience while solving the problem (Cohen, Manion, & Morrison, 2000). Examples of questions were what was the dynamic in your group? Did you learn anything from your peers? Do you think any other group member learned anything from you? Did you compare your capabilities to group members? Do you think working in a group produced a better solution? Using the transcripts of student experiences, thematic analysis was employed to identify patterns of themes according to Braun and Clarke's (2006) six-phase approach. It was intended that student problem-solving processes would be further explored in focus group discussions and cross referenced with the main findings of the written solutions analysis. The focus group discussions were facilitated by a member of the research team who was not involved with the delivery of the module.

Results

Part A: Volume of gas

Student solutions were analysed to investigate if problem-solving processes were evident in their answers (Table 4). In 2014, 40 student group solutions submitted their answers, 68% of these solutions used Method One. In 2015, 42 student groups submitted their answers, 48% of solutions used Method One. All of the Method One solutions identified that the backpack was of a cylinder shape, therefore scoring 100% on the EU category EU1 (process mapped onto Table 2). The second understanding and exploring process EU2 required the students to identify that the dimensions of the backpack could be estimated. In 2014, 81% of solutions provided evidence that they recognised this information from the question. Similarly in 2015, 80% of solutions displayed understanding and exploring process.

In terms of Method One, in 2014, only 39% ($N = 28$) of the student solutions indicated that they had used MR progresses by checking their estimated dimensions. This was distributed as follows:

- solutions used referenced values of cow dimensions to estimate the dimensions of the backpack;

Table 4. Method One, percentage of student solutions that displayed student problem-solving processes.

Year	EU (%)[a]	EU (%)[b]	MR (%)	RF (%)	PE (%)
2014	100	81	39	100	78
2015	100	80	30	100	90

[a]First instance.
[b]Second instance.

- solutions stated that an actual cow back was measured to estimate the dimensions of the cylinder;
- solutions used a referenced value of an average man's height to calculate the values of the cylinder.

The remaining solutions did not indicate that they checked their estimations of the dimensions in any way, therefore did not explicitly indicate MR processes.

In 2015, only 30% ($N = 20$) of the student solutions displayed MR processes by checking their estimated dimensions, the majority did not justify. Solutions that were classified as showing MR process contained:

- referenced values of cow dimensions to estimate the dimensions of the backpack;
- a referenced value of an average man's height to calculate the values of the cylinder.

In 2014 and 2015, 100% of the solutions correctly selected the volume of a cylinder formula to calculate the volume of the backpack, indicating representation and formulating processes. In 2014, 78% of solutions correctly inserted the values into the volume of a cylinder formula, displaying accurate PE processes. Solutions were categorised as insufficient in PE processes for two reasons. For example, solutions inserted their estimated diameter of the cylinder instead of the radius into the formula. In 2015, 90% of solutions correctly inserted the values into the volume of a cylinder formula, exhibiting PE processes. Students were classified as not showing PE processing in stances where they incorrectly inserted a diameter value instead of a radius value, and incorrectly converted units.

Concerning Method Two, problem-solving processes outlined in Table 2 were analysed. In 2014, 32% ($N = 40$) of the student solutions assumed a value for the amount of gas produced rather than to calculate it. In 2015, 52% ($N = 42$) of the student solutions also choose this method. By recognising that they had to search for the information relating to the amount of gas, 100% of students displayed EU of the information represented in the problem in both academic years (Table 5). In 2014, only 17% ($N = 12$) of students showed MR processes by comparing their assumption to a referenced value. The remaining students assumed a volume or number of moles of gas that were present in the backpack without justifying their answer with a referenced value. In 2015, 32% ($N = 22$) of the students critically evaluated their assumptions displaying MR processes by justifying their assumption.

Part B: Energy needed for family home

In 2014, 95% ($N = 40$) of the student solutions displayed EU processes by presenting a value for the amount of energy needed by a family home (Table 6). The remaining 5% of solutions did not indicate this process as they simply calculated how much energy

Table 5. Method Two, find volume by assumption, student problem-solving processes.

Year	EU (%)	MR (%)
2014	100	39
2015	100	30

Table 6. Energy required by the home.

Year	EU (%)	MR (%)
2014	95	55
2015	98	38

could be released from methane. Only 55% ($N = 40$) of the solutions indicated monitoring or reflective processes by justifying their value with a referenced value.

In 2015, 98% ($N = 42$) indicated EU processes by providing a value for the amount of energy used by a family home. The remaining solutions did not use any value; they merely worked out the energy produced by methane. Only 38% used a referenced figure for the amount of energy an average household uses. The remaining solutions presented a value without referencing it to justify its suitability.

Part C: How much energy will be released from a quantity of methane

In 2014, 90% ($N = 40$) of the solutions indicated that they contained RF processes (Table 7). Approximately, 88% ($N = 40$) of the students choose to use the combustion of methane to calculate how much energy was available in the amount of gas; 2% of solutions used a referenced value from an internet source (one cow's methane equals 4.8 kW h). The remaining 10% used various methods but did not build a coherent representation of what relationships they were expressing. For example:

- solution used the heat of combustion value per mole, incorrectly labelled it specific heat capacity,
- solutions gave no explanation of the method or relationship used. For example, converting the volume in litres to energy in megajoule.

Student solutions were analysed regarding the explicit presence of PE processes. A solution would display this process if it showed an effective strategy for finding the amount of energy release by methane. In total, 73% of solutions displayed a correct strategy, 27% displayed incorrect strategies. Examples of solutions that were considered incorrect:

- calculated the number of moles, for no purpose as it was not relevant for their strategy,
- assumed the number of moles, without any justification as to why they were using that specific amount as part of their strategy,
- found the specific heat capacity of methane,
- converted grams to litres without justification or any known method used.

Table 7. Energy released by methane, problem-solving processes evident.

Year	RF (%)	PE, first instance (%)	PE, second instance (%)
2014	90	73	90
2015	84	81	90

Student solutions were analysed regarding their effectiveness in carrying out their chosen strategy. Approximately, 90% of the solutions correctly executed their strategy, 10% did not. The 10% that did not execute their strategy had incomplete or missing answers.

In 2015, 84% ($N = 42$) of the solutions indicated that they contained RF processes by identifying the combustion of methane value per mole or per kilogram. Sixteen percent of the solutions did not display RF processes as they did not select relevant scientific principles. For example,

- solutions used an unknown or unjustified conversion method. For example, one stated that 1 m^3 of methane = 10 kW h. This value was not rationalised or checked in any way,
- solutions incorrectly used the heat of fusion of methane to calculate the amount of energy that was released.

Solutions that included a coherent strategy for finding the amount of energy released by methane were considered to have displayed PE strategies. In total, 81% of the solutions displayed a correct strategy, 19% displayed incorrect strategies. An overview of the incorrect strategies solutions displayed were

- solutions calculated mass for no purpose,
- solutions assumed an amount of gas that was different from first calculation with no justification,
- solutions multiplied the number of moles of gas by fusion of methane value,
- solutions stated the Ideal Gas Law to calculate volume, however, did not use it to calculate volume. The pressure of the gas was also calculated for no logical reason.

Student solutions were analysed regarding how they performed their strategy to investigate if PE processes were evident. In total, 90% of the solution executed their strategy correctly, 10% of the solutions did not. The 10% of solutions that did not correctly execute their strategy consisted of:

- solutions used different volumes in different parts of their solution,
- solutions had an incomplete solution missing this part.

Part D: Solution conclusions

In 2014, 73% ($N = 40$) of student solutions formed a logical conclusion where they compared the values of energy that were produced by cow/cow herd to the amount of energy needed by the family home. Overall, 15% of the solutions formed a conclusion but did not compare the values; 6% of the solutions did not form a conclusion, they just completed the calculations; 3% of solutions compared the energy produced by the cow herd to energy required by a home; however, the units were not the same, therefore, they were not logical; 3% were illogical as they had a different values compared in the conclusion to the calculations. It was concluded that 27% of the solutions did not communicate their findings in a manner that indicated MR processes.

In 2015, 83% ($N = 42$) of solutions formed a logical conclusion where they compared the value of energy that was produced by cow/cow herd to the amount of energy needed by the family home. Similar to the previous academic year, 12% of the solutions did not compare the value of energy needed by the home to the energy produced by the cows, 5% of solutions had an illogical comparison, for example comparing values with different units. It was determined that 17% of the solutions did not communicate their answers in a means that exhibited MR processes.

Peer interaction and problem-solving

Peer interaction can act as a means of aiding students developing their problem-solving processes in an ill-structured task. In 2015, students ($N = 95$) were surveyed to investigate if they worked independently or collaborated in class sessions (Table 8). The majority of students (58%) stated that they worked independently, combining their separate parts at the end of the class to submit a complete solution. Just 24% of the students answered that they discussed each part of the solution before combining to submit. This provides evidence that although students were assigned groups and were expected to work collaboratively on the problems, only 24% of the students reported that they reviewed group members completed sections prior to submission.

To further investigate student problem-solving processes, student focus group discussions were facilitated to investigate students' experience of collaboration during the formation of their solution to the problem. It was hypothesised that low levels of intermediate student monitoring and reflection process were due to low levels of peer discussion and interaction when creating their written solutions.

Student ability emerged as a factor in the level of participation and collaboration between group members. Approximately, half of the students in the focus groups reported that having students of a lower ability in a group decreased collaboration; other students stated it increased collaboration. One student indicated that certain group members did not attempt to complete any parts of the work and when they did try they are unable to participate. He stated that one member of a group had not completed any parts of a problem for the whole semester. Another student stated that he did not participate when it came to the calculations.

> With the calculations sort of thing I wouldn't be very comfortable with them because I know that I wouldn't be able to get a good answer. And I would sort of be afraid that if I did it and I'd do it wrong. I just prefer to let someone else do it and do it properly.

Table 8. Survey question: When you met for the two-hour class session on a Tuesday.

Response	Frequency
(a) Did you work independently and combine separate parts to complete assignment?	58%
(b) Did you discuss each part and then combine to complete assignment?	24%
(c) Use some other method?	3%
	15% students selected both (a) and (b)

This particular student agreed that it would be more effective for the group if they all stuck to their own 'strengths', working individually. Other students commented that having peers with a higher capability helped them understand something they previously could not. Another student commented that they helped group members who were unable to understand certain parts, for the good of the group's success 'if you see someone else struggle I don't know why you wouldn't say something to them if it's going to affect your grade'. It is important for students to realise that the success of their group is a combined effort, not an individual one.

The most reported instances of collaboration were in relation to students having difficulties with the calculations. For example, 'No one in my group was actually good at calculations so we always try to do those bits together'. In this situation, as no student in the group felt that calculations were a strong point, they were required to collaborate to complete that part of the problem. Students commented on how they discussed possible mathematical strategies. Another student commented 'For the maths part you just ask people what they thought and what they did. Once you figure out the method to do it you can do it yourself then'. This indicates that students collaborating helped these students to develop their PE processes. Students also reported that the ill-structured nature of the problem facilitated peer discussions to compare their interpretations of the question. One student explained 'I found the hardest part of the whole thing was actually figuring out what you had to do, not doing it, figuring out what they are asking you'. Students commented that it was difficult to know what approach to take as the question was left open to interpretation. One student noted the value of having peer support in relation to the interpretation of the question 'You can get someone to read one question and a different person will read into it a different way so you are getting these different viewpoints and ideas that you wouldn't come up with yourself'. This was a positive response as it was hoped that the combined effort of the students rather than individual efforts would be required to solve the problem.

A common theme that converged with the student survey question was that students did not discuss their completed section prior to submission of the complete solution. One student remarked 'We kind of split it up first. You know you are doing section A, you are not going to look at section D. Someone else has that done'. The idea that students stuck to the areas that they identified as their strengths was communicated by students repeatedly.

> Everyone just picked the part that they were good at and they did it. Whoever is good at that part does that part and so on so we didn't really help each other out; we stuck to our own stuff.

In some cases, students felt that they were discouraged from collaborating in their groups as they all had assigned themselves different tasks to complete. One student commented that because the other members of her group were working independently to complete their part of the problem, she felt that she could not discuss her section with group members.

At no point during any of the focus groups did a student describe an instance where they monitored or reflected on each other's work. On the contrary, one student explained that because they were all working separately, there was no opportunity to monitor other students work. He stated:

> We looked at it at the end but it wouldn't really matter, whoever did that part if they did it right or wrong it would be too late to change it anyways because there would only be a little bit of time left. So even if I spotted something wrong, you wouldn't have time to change it all.

Another student explained that he did not critique another students work if he believed that they were putting forward inadequate work as opposed to incorrect work 'If it's a situation where they (group member) don't understand, then maybe I might say something but if it's a something where they probably do understand and they are aware that it is subpar then I wouldn't say anything'. This highlights the need to implement an accompanying exercise with the problem that requires students to state what critiques they made to their group members section. The importance of students MR on each other's work needs to be emphasised during the task to promote self-regulation of their work.

In 2015, eight groups consistently showed MR processes throughout their solutions. Nineteen of these students answered the survey question in Table 8. Approximately, 42% ($N = 19$) of these students stated that they worked independently and combined separate parts to complete assignment rejecting the hypothesis that student discussion of the solution prior to submission would increase MR processes. Approximately, 16% of these students discussed each part prior to submission and 42% stated that they worked independently and discussed parts before submission. Interestingly of the eight groups that consistently showed MR processes in their solutions, four were from the same tutorial group. The other four groups were dispersed between the other three rooms. This would lead to the assumption that the tutor's interaction with the students may have aided students displaying MR processes in their solutions. In light of this finding tutor mentoring will be provided to support tutors in their role of advocating MR processes by encouraging students to justify their assumptions, establish coherent arguments and critically evaluate their groups' solution.

Discussion and conclusion

Applying a theoretical framework to assess student written solutions provided evidence of students' problem-solving processes. It is proposed that making deficiencies in students' problem-solving processes explicit to students can focus their development of specific absent problem-solving processes in their written solutions. Mapping the problem-solving processes onto specific student solutions supports the practice of formative assessment. The implication of this research is that assessing student problem-solving using the problem-solving processes framework is a method of generating valuable feedback to students to indicate if their written problem-solving strategies are progressing from question to question. It is important to note that this research analysed group solutions, not individual student work. The methods presented in this study could also be used to assess individual student written solutions.

The results of this analysis indicate that high levels of EU processes were evident in student solutions. Focus group sessions provided evidence that students discussed their interpretations of the question. Collaborative work may have been the catalyst that encouraged such high scores in EU, particularly as the problem was ill-structured. The exchange of learner's interpretations may result in the analyses of different perspectives and understanding.

The strong levels of RF in student solutions indicate that students drew on their knowledge of science concepts and principles to solve the problem. These findings support the work of Ge and Land (2004) who report that students working on a problem collaboratively surpassed individual students' problem representation. This is an important finding as research conducted by Chi, Feltovich, and Glaser (1981) investigated the difference between how novice and expert problem-solvers form problem representations. They state that experts' problem representations are based on physics principles, whereas novice problem representations are based on the problem facts.

Considerable levels of PE processes were evident in student solutions which highlight students' competence in formulating and implementing a plan to solve the problem. Focus group discussions revealed that students collaborated to discuss potential strategies to solve problems. Social constructivist theory agrees that social environments strongly impact learning (Vygotsky L., 1962). Liu and Matthews (2005) state that social and situated constructivism are derived from Vygotsky's research. Parallel to the assumptions of situated constructivism it presumes that the learner actively constructs meanings socially.

Absent problem-solving processes were similar in both academic years, with students showing low levels of MR processes at the intermediate stages of problem-solving. Poor justification of student assumptions was the main cause for low levels of MR processes in student solutions. These results highlight the need for students to reflect on their written solutions and specifically indicate their reason for an assumed value (Shin, Jonassen, & McGee, 2003). Based on these findings, modifications can now be made to improve written problem-solving practices, with the intention of students developing a complete set of problem-solving processes in their solutions. In future iterations of students completing this problem, groups will be given a 'reflection tool' before they submit their solutions. This tool will ask students to identify areas where assumptions are justified in their solutions. The intention of this tool is to direct students to reflect on their completed solutions so that they can identify if justifications are missing from their solutions, hence allowing them to reflect on the solution. Previous opportunities for students to develop justification skills may have been limited. The problem used in this module had missing information therefore it required students to understand the problem situation and assume values, justifying their selection. It was the justification of student assumptions that were lacking in student solutions. Justification of an assumed value is particularly important in an ill-structured problem as it indicates that the student has put forward a rational reasoning of why they chose a value (Jonassen, 1997). Students need to explain an assumption as an assumption without a justification that does not put forward a credible argument. In science, arguments consist of a claim and the evidence to back up that claim (Erduran, Simon, & Osborne, 2004). Without the justification (evidence), the assumption has no meaning. This is not merely an expectation of the authors, this is based on argumentation theories.

Problem-solving processes can be identified from student written solutions; however, some solutions may not entirely provide evidence of the strengths and weaknesses of problem-solvers. This research, however, differs from research where student class work is analysed, students are given the opportunity to submit their solutions after a week of research and contact with their group members, facilitating them constructing a comprehensible solution. Students were explicitly asked to justify their assumptions and calculations in the instructions of this problem and it was further highlighted in the grading scheme.

Finally, this problem was deemed as an ill-structured problem as it has missing information and supposedly had multiple possible solutions. In reality, however, student methods to solve the problem were similar in both academic years. This may have been due to students studying similar science modules, so that students drew on comparable domain knowledge of science. One cannot be sure of the level of knowledge or disciplines that may be aroused when students solve an ill-structured problem (Hisschemöller, Hoppe, Dunn, & Ravetz, 2001).

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Notes on contributors

Regina Kelly, PhD, is a post-doctoral researcher in Centre for the Advancement of STEM Teaching and Learning (CASTeL) at Dublin City University. She completed a PhD on the key motivational factors that influence participant performance and attitudes to physics in undergraduate education. Her research interests focus on science education with a special focus on physics education, problem-based learning, scientific argumentation, student perspectives on the aims and values of science and community engagement of science.

Eilish McLoughlin, PhD, is a senior lecturer in the School of Physical Sciences and is Director of the Centre for the Advancement of STEM Teaching and Learning (CASTeL) at Dublin City University, Ireland. She holds a PhD in experimental physics. Her research interests focus on teaching, learning and assessment of science (physics) including use of inquiry and interdisciplinary learning and effective use technology in education.

Odilla Finlayson, PhD, is a senior lecturer in the School of Chemical Sciences, a member of CASTeL and chair of BSc and MSc Science Education programmes at Dublin City University. Her PhD was in the area of heterogeneous catalysis. Her research interests are in engaging pedagogies for science teaching and assessment; these currently include CASE, visualisations, inquiry and integrative approaches, including laboratory activities.

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