Research-based worksheets on using multiple representations in science classrooms

by Matthew Hill and Manjula Sharma

Abstract
The ability to represent the world like a scientist is difficult to teach, it is more than simply knowing the representations (e.g. graphs, words, equations, and diagrams). For learning to take place representations must be introduced to students meaningful ways, linked to the content that they will be learning, and supported by explanations as to why the representations play an important role in understanding. Unfortunately, developing teaching tools for representations is not easy; there has not been much research. This article draws on work on teaching science concepts to iteratively develop a simple, interactive tool that can be used in a school setting with immediate results. It includes a framework that can be used to teach a wide range of representations from various science disciplines. Our object was to research this process - how design can be done effectively. Ultimately we present a set of worksheets as an example of research-based instructional design which support year 12 physics students engaging with (1) Free-body diagrams and (2) Equations of energy.

1. Introduction
Duit (2007) describes three significant issues related to science instructional design.

“First, development needs to be fundamentally research based and needs serious evaluation employing empirical research methods.

Second, development should be viewed also as an opportunity for research studies to be included.

Third, improving practice is likely only if development and research are closely linked.”

(Duit, 2007, p9)

Our research endeavors to demonstrate consideration of each of these issues in the design of a framework, and worksheets to teach science representations to high school students. While the immediate context is year 12 physics, the study has direct comparisons and implications for teaching various sciences at a range of student levels.

2. Literature: Development needs to be fundamentally research based
We carried out a literature search on various aspects of multiple representations and instructional methods for improving student learning of multiple representations. These are presented below.

2.1 Using Multiple Representations in Science
Scientists represent the world through a combination of verbal, visual and symbolic representations among others (Gilbert, 2004). Etkina, Van Heuvelen, White-Brahmia, Brookes, Gentile, Murthy, Rosengrant, and Warren (2006) describe this as the first of seven abilities that science students must be capable of. From an early age children are taught how words, pictures and numbers can represent things around them. As their level of science learning experience increases the sophistication of the representations also increases. Words become explanations, pictures are now graphs and diagrams, and numbers are superseded by algebra and equations. The ability to use various types of scientific representations coherently, efficiently, and effectively is referred to as representational fluency (Bieda
Helping students experience multiple representations is important in science as not only does knowing multiple representations improve learning, but representational fluency is essential for problem solving and communication as a scientist. However, “before students can benefit from using a representation, they need to learn the conventions that regulate the way the representation is used, how it relates to reality and how it relates to other representations” (Nistal, Van Dooren, Clarebout, Elen, & Verschaffel, 2009), p628. Various instructional methods could be used for realizing the above. We decided to focus on worksheets as they are commonplace and provide the opportunity for distilling an overall framework.

2.2 Instructional Methods: Experiencing Multiple Representations through Worksheets

From our review of the literature we highlight four helpful studies which captured research findings, provided strategies for instructional methods, and had real data supporting their work. Furthermore, the strategies could be purposefully integrated into worksheets, bridging the gap between research and classroom practice in a meaningful way. The lessons for representations-based worksheet design are:

1. Experiencing conceptually based scientific material in a module (similar to a worksheet) before a class improves learning during the lecture or class. Seery and Donnelly (2012) demonstrated this with university chemistry students.
2. Representations-based teaching worksheets are effective at university when there is a set structure which includes explaining the purpose of the modules to students (Jackson & Johnson, 2013).
3. A strongly-directed approach to teaching representations has a greater effect on student learning. A strongly-directed approach involves explicitly directing students how and when to use a particular representation. (Kohl, Rosengrant, & Finkelstein, 2007).
4. One way of learning the affordances (or helpfulness) of representations for a particular situation is to give students the same problem to be solved multiple times with different representations. (Dufresne, Gerace, & Leonard, 2004)

These lessons were used to create 15 minute worksheets designed to allow students to experience physics material prior to class discussion (cf. Seery & Donnelly, 2012). The lessons used a set structure adapted from Jackson and Johnson (2013) and utilised validated approaches to teaching representations (Dufresne et al., 2004; Kohl et al., 2007).

3. Research Design: Development needs serious evaluation employing empirical research methods

This section describes the development process, data gathered through two trials and how evidence was used to refine the worksheets.

3.1 Purpose of the Study

1. To create research based worksheets in two topics to aid teaching of multiple representations
2. To empirically demonstrate that the representations-based worksheets can impact student practices
3. To provide a framework for developing representations-based instruction in other topics and disciplines.

3.2 The worksheets

Since Seery and Donnelly (2012) had based their work on conceptual material (chemistry content knowledge rather than representations), we decided to create two sets of worksheets. One was on physics concepts which we call the “concepts worksheets” and the other on multiple representations which are the “representations worksheets”. For the concepts worksheets, we drew on the vast array of literature on alternative conceptions and conceptual understandings. Both sets of worksheets were
created on the topics of forces and energy, therefore a total of four worksheets were created (Table 1). Appendix 1 has links to all four final worksheets.

Table 1: The four worksheets. Two on the topic of forces, two on the topic of energy.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Representations Worksheets</th>
<th>Concepts Worksheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forces</td>
<td>Free-body diagrams</td>
<td>Tension and friction</td>
</tr>
<tr>
<td>Energy</td>
<td>Equations of energy</td>
<td>Kinetic and potential energy</td>
</tr>
</tbody>
</table>

Each pair of worksheets was on the same topic for two reasons. Firstly, the content was to be parallel as both were to be helpful in preparation for a lesson on the topic (forces or energy). The content was equivalent, but very different in that representations worksheets would address student learning difficulties with regards to representations while concepts worksheets would address conceptual difficulties which abound in literature. Secondly, this allowed for a common question to be embedded across both worksheets to compare student learning from each worksheet.

Each worksheet had three parts; information where the representations or concepts were explicitly introduced, questions where ideas were to be internalized through application in two questions specific to the information in each worksheet and one common question that was appropriate to the information from both worksheets, and reflection which included two questions designed to promote students’ metacognition and self-evaluation. The template in Figure 1 shows the structure, the commonalities, and differences between the representations and concepts worksheets.
### Figure 1: Template for a 15 minute worksheet introducing students to scientific representations or concepts prior to further instruction. Can be used for various scientific disciplines.

<table>
<thead>
<tr>
<th>Representations Worksheet</th>
<th>Concepts Worksheet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Part 1: Information</strong></td>
<td><strong>Part 1: Information</strong></td>
</tr>
<tr>
<td><strong>What to master:</strong></td>
<td><strong>Key terms to know by the end of the session:</strong></td>
</tr>
<tr>
<td>A list of up to 3 skills</td>
<td>A list of up to 5 linked physics concepts</td>
</tr>
<tr>
<td><strong>Why you need to know this:</strong></td>
<td><strong>Why you need to know these concepts:</strong></td>
</tr>
<tr>
<td>Explaining how the skills can be helpful in physics</td>
<td>Explaining how the concepts are important to physics</td>
</tr>
<tr>
<td><strong>How to master the skills:</strong></td>
<td><strong>What you need to know:</strong></td>
</tr>
<tr>
<td>Strongly directed/explicit instruction on how to use the representation</td>
<td>Clear concise definitions, explanations and applications of the concepts</td>
</tr>
<tr>
<td><strong>Part 2: Questions</strong></td>
<td><strong>Part 2: Questions</strong></td>
</tr>
<tr>
<td><strong>Question 1R:</strong></td>
<td><strong>Question 1C:</strong></td>
</tr>
<tr>
<td>Question requiring</td>
<td>Question requiring</td>
</tr>
<tr>
<td>representational</td>
<td>conceptual</td>
</tr>
<tr>
<td>use/thinking</td>
<td>knowledge/thinking</td>
</tr>
<tr>
<td><strong>Question 2R:</strong></td>
<td><strong>Question 2C:</strong></td>
</tr>
<tr>
<td>Question requiring</td>
<td>Question requiring</td>
</tr>
<tr>
<td>representational use/thinking</td>
<td>conceptual</td>
</tr>
<tr>
<td><strong>Question 3:</strong></td>
<td><strong>Question 3:</strong></td>
</tr>
<tr>
<td>(Common Question)</td>
<td>(Common Question)</td>
</tr>
<tr>
<td>Question appropriate to</td>
<td>Question appropriate to</td>
</tr>
<tr>
<td>information from both</td>
<td>information from both</td>
</tr>
<tr>
<td>worksheets</td>
<td>worksheets</td>
</tr>
<tr>
<td><strong>Part 3: Reflection</strong></td>
<td><strong>Part 3: Reflection</strong></td>
</tr>
<tr>
<td>How well do you think you know when and how to use Representation? (Likert) Allows students and teachers to identify whether further work needs to be done in this area</td>
<td>How well do you think you know the concept of Concept? (Likert) Allows students and teachers to identify whether further work needs to be done in this area</td>
</tr>
<tr>
<td>How helpful was this information for your study of physics this year? (Likert) Helps students connect the instruction to the wider course as a whole</td>
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</tr>
</tbody>
</table>

#### 3.3 Determining effectiveness of the worksheets

A critical question in instructional design is how to determine its effectiveness. Here we capitalized on another opportunity for research (the second of Duit’s (2007) significant issues in educational design). We had the students complete the common questions twice, once before doing the worksheets and the second time as part of the worksheets. This meant that we could ascertain if completing the worksheet produced change in student responses. Hence the common questions were a ‘measurement’ tool, as were the reflection questions. We also held a focus group discussion after the worksheets. Consequently, we had three sets of data to be analysed:

1. Common questions (including comparing answers pre and post worksheet instruction, and comparing answers of representations students with concepts students)
2. Reflection questions
4. Implementation

In the spirit of Duit’s third issue (Duit, 2007), we closely linked development and research. Hence two trials were undertaken to develop and assess the worksheets. Each trial followed the structure of table 2.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Representations Students</th>
<th>Concepts Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Minutes</td>
<td>Common questions 1 &amp; 2</td>
<td>Worksheet 1: Understanding tension and friction (Contains common question 1)</td>
</tr>
<tr>
<td>15 Minutes</td>
<td>Worksheet 1: Free body diagrams</td>
<td>Worksheet 1: Understanding tension and friction (Contains common question 1)</td>
</tr>
<tr>
<td></td>
<td>(Contains common question 1)</td>
<td></td>
</tr>
<tr>
<td>15 Minutes</td>
<td>Worksheet 2: Equations of energy</td>
<td>Worksheet 2: Kinetic and potential energy (Contains common question 2)</td>
</tr>
<tr>
<td></td>
<td>(Contains common question 2)</td>
<td></td>
</tr>
<tr>
<td>10 Minutes</td>
<td>Focus group discussion</td>
<td></td>
</tr>
</tbody>
</table>

Data were analysed after the first trial with a group of students, changes were made to the worksheets or questions and the second trial was conducted with a new group of students. Therefore the worksheets were iteratively developed and critically analysed in order to produce a set of research-based instructional material with demonstrated effectiveness.

4.1 The Sample

Each trial was conducted at different schools, with different groups of year 12 physics students (in their final year of High School instruction). Both schools are classified as independent, non-selective, K-12 schools in the Sydney region. A total of 32 students from School A completed either the representations or the concepts worksheets. This formed the first trial in the development. School B involved fewer students as some students associated with the class were completing the course by distance. Responses from 13 students from School B were collected.

5. Results: Common questions

In this section we present the results and discuss how evidence from trial 1 was used to improve the worksheets for trial 2. Results of trial 1 indicated limited benefit of the worksheets, but trial 2 revealed that the modified worksheets were beneficial for student learning. This clearly affirms Duit’s reminder that experimentation and evaluation is crucial to the development process.

5.1 Worksheet 1: Forces

Figure 2 shows the common question from the forces worksheets. The question was seeking four main forces; weight, friction, a pulling force from the rope (tension) and a normal/restorative force from the ground on the box. Both sheets were designed, in different ways, to help the students to identify these forces. We expected students who had completed the concepts worksheet to more readily identify tension and friction by name, and the students who had completed the representations worksheet to be more likely to identify the often forgotten normal force.
To illustrate changes in student responses before and after completing the worksheet, we calculated gains. The gain is increase in the percentage of students identifying a particular force after completing the worksheet, divided by the percentage of students who did not identify the force before instruction. For example, 21% of the concepts students had identified tension by name pre-instruction and 79% had not. After instruction those 79% of students had all also identified tension, giving a gain of 100%.

In figure 3 the size of the arrow shows the gain with arrows pointing to the right indicating positive gain, or more students identifying the force.

**Trial 1: Student gains in force identification post instruction**

![Force Identification Chart]

From figure 3, we note that all concepts students identified the pulling force as “tension” post-instruction; the gain is 100%. This occurred in two categories for the concepts worksheets, but there was no gain in the other categories. For the representations students, two categories registered small positive gains (including the elusive normal force). However, there were two which had negative gains as fewer students identified the force post-instruction.
In summary, these results indicate that the concepts worksheet is effective at scaffolding student learning. However there is limited indication of the benefit of the representations worksheet. This was therefore the worksheet that needed to be developed prior to the second trial.

Specific changes to the representations worksheet on free-body diagrams were made. The Information and Questions sections were made more strongly directed (Kohl et al., 2007). Explicitly, instead of pointing to features of a free-body diagram and giving examples, a four step process of how to draw a free-body diagram was provided, followed by one example with a 90 word explanation of the image.

The new worksheets were used in trial two with the same common question and analysis. See figure 4 for gains.

![Trial 2: Student gains in force identification post instruction](image)

Figure 4: The gain in students identifying forces for common question 1 during trial 2 showing much larger gains for the representations worksheet than during the first trial.

The concepts worksheet remained relatively unchanged from trial 1 to trial 2 and so unsurprisingly, there was 100% gain for pulling force and a large gain of 60% for tension. The students who did not use the word tension communicated the forces using a diagram rather than words which accounts for less than 100% of students naming the force “Tension”. Rather pleasingly, this group of students also had a 100% gain in identifying friction.

In the case of the representations students there is an increase in almost every category but most distinct from the concepts students is the increase in students identifying weight and identifying the normal force. The difference in student responses suggests that the students with representations instruction were more likely to visualize the situation through the lens of a free-body diagram resulting in greater increases in forces identified by students with representations instruction than those with concepts instruction. This is especially true for identifying the normal force which often is remembered after drawing a free-body diagram requiring the balancing of forces.

5.2 Worksheet 2: Energy
Figure 5 shows common question 2 on energy used in trial 1. The goal was to see which representations students would use in their answer, especially whether the representations students would use more sophisticated representations of equations or diagrams.

**Question 3:**
Write out a plan (i.e. What steps you would take) in the box below for how you would solve the following problem: A car is travelling along a level icy road with no friction (that is, no friction) and comes to a rise 20m long at an inclination of 25 degrees. What minimum speed does the car need to be going at the bottom of the slope to reach the top?

Figure 5: The common question for the Energy worksheets. This is the question used in trial 1 which was then modified for trial 2.

Many students found this question confusing and were unable to provide coherent answers. The typical response was to draw a picture and write a long list of equations, many not suitable to solve the problem. For this question, student responses were coded as utilizing one or more of three representations – words, equations, or diagrams. It was found that students completing both worksheets used similar representations in their answers (figure 6).

![Figure 6: Percentage of students using particular representations (words, diagrams and equations) to answer the common question of the energy worksheets (trial 1)](image)

In the case of the worksheets on forces described earlier, we had modified and improved the Information section of the worksheet. For the worksheets on energy there is a different issue as the common question is not distinguishing between representations students and concepts students. Therefore, in consultation with experts in education research, the common question was made more sensitive. Therefore, for trial 2, a rollercoaster travelling in a loop rather than a car sliding without friction was used for the common question. The premise behind the question was fundamentally the same, but the content was changed and an image was included. The new common question for trial 2 is included as figure 7.
Figure 7: The common question for the energy worksheets (trial 2)

Figure 8 shows the results of trial 2. Concepts students predominantly used words in their answer while representations students were more likely to draw or refer to a diagram and to use equations in their response. These representations are regarded as more sophisticated than simply a words-based response in the research literature (Dufresne et al., 2004; Gilbert, 2004). These data reveal that the modified question was sensitive to insights gained by students from the different worksheets. In particular, that the representations students were able to use more diagrams and equations in their problem solving methods.

Figure 8: Results of energy worksheets common question (trial 2). Percentage of students using the representations of words, diagrams or equations in their responses.

6. Results: Reflection Question and Focus group discussion

While student perception of their own learning does not always correlate with actual learning (Spinello & Fischbach, 2008) the students opinions on the worksheets and their feedback for improvements was a valuable resource. We will make brief mention of the results that impacted worksheet development.

6.1 Reflection questions:
Typically students found the worksheets helpful for their study of year 12 physics. On average 86% of students indicated that the worksheets were at least partly helpful. Few students indicated that the worksheets were “very helpful” but we predict that this is because there may be limited perceived helpfulness of an exercise that only lasts 15 minutes. In addition, the worksheets were not designed to be a complete lesson, rather to put students into the right frame of mind for a regular class on the topics of forces or energy.

5.3.2 Focus group discussions:
During class discussions after completing worksheets on both topics (forces and energy) the students as a group were asked questions including: Did they have enough time for the worksheets, what did they learn, and what did they find confusing? These were conducted after each trial.

Results across the board indicated that the worksheets were of the right length, with some students responding that there was too much time for the forces worksheet. There is potential for greater content but one should be careful not to put too much into any worksheet.

Students were able to articulate a variety of new things that they had learned, despite the limited content. Students who completed the concepts worksheets felt that they had been reminded of the definitions of certain concepts and were interested in the particular fact that “kinetic friction is less than the force of the static friction” (Concepts Student). Students who completed the representations worksheet recognised the process and problem solving strategies that they had learned; “the conservation of energy, I wouldn’t generally think in that way of using an equation... for question A (common question 2 given before instruction) I actually wrote an equation without realizing it but then on part B (common question 2 given after instruction) I realized “oh” and changed it so that it used the law of conservation of energy” (Representations Student).

When asked what they found confusing, multiple students remarked after the first trial that they were still confused about free-body diagrams. No students made this comment after the second trial when completing the updated and simplified worksheet. There were other terms that needed clearer definitions including “static friction” and “work”.

7. Discussion
Instruction must incorporate both teaching and research. This is the fundamental idea behind the three important principles identified by Duit (2007). While there will always be those who specialise in one of these two areas, it is important that teachers understand and participate in research and that researchers do not see themselves independent from teachers.

7.1 Demonstrating how research-based representations worksheets can impact student practice
Classroom teachers recognise this as a non-trivial task. After two trials, we were able to show that by completing a 15 minute worksheet on representations students were more likely to use diagrams and equations in problem solving than students learning about related physics concepts. We cannot hope to completely change the students representational practices with such a short worksheet, however these students are now prepared to view further class instruction (or homework) through the lens of the particular representation introduced, resulting in improved learning in class (Nistal et al., 2009).

Further study is needed to investigate the long term impact of regular, brief representation experiences used in this study. Already, research at a university level by the authors has indicated long term gains in both representational fluency, and conceptual understanding as a result of similar activities.

7.2 Providing a template and process of how teachers can develop representations-based instruction suitable to their discipline
This was achieved in two ways. Firstly, the explicit structure of representations-focused (and concepts-focused) worksheets set out in figure 1 which has shown to have the potential to be effective through this study. The second way is through demonstrating the development process which
including reflective assessment of the worksheets and student answers. In the case of the worksheets on the topic of forces, the content of the worksheet on free-body diagrams needed to be modified after trial 1. The same common question was able to be used. However, we demonstrated how it is not always the content that needs modification, in the case of the worksheets on the topic of energy, the common question wasn’t sensitive enough to measure differences in student learning. In this case, the question had to be changed. Both of these are common problems to address which are encountered in research.

Through taking the template of the worksheet structure, and following the model set out in this paper, teachers from varying scientific disciplines are further enabled to produce research-based, tested, instructional material for their students. Using the template, worksheets they could be developed as needed for particularly “representationally rich” topics and “conceptually rich” topics for local contexts.

8. Conclusion

We have highlighted and demonstrated key elements of instructional design. A set of worksheets that can be used to teach students representations in physics, a template for worksheet design particularly novel in the case of the representations-focussed worksheets, and an example of integrating research and teaching applicable to any lesson planning or design are included.

Appendix 1:

Forces Worksheets
Concepts – Understanding Tension and Friction
Representations – Free Body Diagrams

Energy Worksheets
Concepts – Kinetic and Potential Energy
Representations – Equations of Energy

References


