Using Representations for Teaching and Learning in Science

Jim Carolan, La Trobe University
Vaughan Prain, La Trobe University
Bruce Waldrip, University of Southern Queensland

Carolan, J., Prain, V., & Waldrip, B. (2008). Using representations for teaching and learning in science. *Teaching Science, 54* (1), 18-23.

Abstract
There is now broad agreement that learners in primary and secondary school science need to know how to interpret and construct the subject-specific ways of representing science activity and knowledge. There is also growing recognition that students are more motivated and learn more when they have opportunities to refine understandings through revising representations. Drawing on various theoretical perspectives and research studies into the implementation of this approach in classrooms across diverse topics, we propose a framework of pedagogical principles to guide teacher use of this representational focus to enhance learning.

Introduction

How we experience and know our world depends on the languages we have for representing these experiences and knowledge. This applies particularly to science, where students are expected to learn a new literacy consisting of scientific accounts of their physical world. For students to develop these new understandings of phenomena they need to learn how to use the particular languages of science (linking appropriate vocabulary and commentary with visual and mathematical modes) to make these new understandings clear to themselves and to others.

To develop these understandings, students are introduced to, and expected to use, diverse representations. These include teacher-constructed and/or provided ones (such as textbook material), as well as students' own representations of concepts, processes and topics. These representations can be further categorized as specific to the domain of science (such as 3D models, tables, graphs, diagrams, science journals, multi-modal reports, and appropriate vocabulary and measurement for specific topics) and generic representations used in the community and classroom. These include the use of everyday language, cooperative small group work, whole-class guided discussion, posters, word walls, power-point presentations, charts, verbal reports, roleplays, debates and narratives. This second group of representations enable students to link meaning-making in their everyday world with meanings in science.

In this paper we draw on theoretical accounts of meaning-making (Peirce 1931-58; Lemke, 2003), recent research on factors affecting cognition (Barsalou, 1999; Grush 2004; Klein, 2006; Schwartz & Heiser, 2006), and classroom studies using a representational focus (Hackling & Prain, 2005; diSessa, 2004; Tytler, Peterson & Prain, 2006) to develop a framework to guide teachers' use of representations to support student learning. We consider principles to guide this approach, including teacher and student roles and interactions.

Theoretical Perspectives

In thinking about the relationship between observing, representing, and meaning-making, consider the case of a young child responding to a simple two-dimensional pictorial representation of two cows (Figure 1). Any spatial, directional and relational meanings are not self-evident in the picture. Learners need to learn the conventions that apply to interpreting this representation as indicating perspective, including the implied distance of the viewer/reader from the cows, and between the cows.

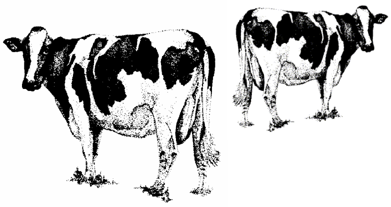

Figure 1: Pictorial representation of two cows

Without guidance, a young child might think that one cow is smaller than the other (Figure 2), and may need support to understand both the conventions that guide interpreting this representation (the role of size and position to indicate distance from viewer) and the meaning of this representation (a herd, rather than cow and calf, or some other relationship).

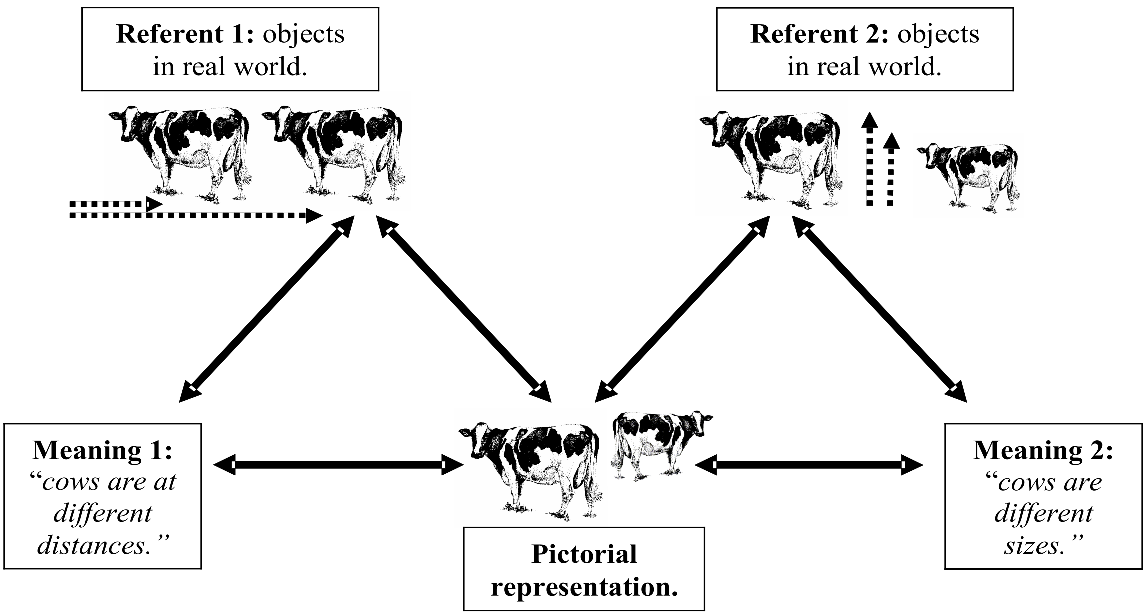

Figure 2: Alternative meanings derived from a single representation.

More broadly, this interpretive capacity can be understood as representational competence (diSessa, 2004), and is crucial to learning in science in primary and secondary school. As noted by Lemke (2003), drawing on Peirce (1931-58), representational competence is about knowing how to interpret and construct links between an object, its representation, and its meaning. A representation becomes a sign when it signifies something (a key idea or explanation) about the object (or referent) to someone (the learner). Meaning-making practices in school subjects, including science, can be understood in terms of Peirce's (1931-58) triadic account of the necessary components of this meaning-making (Figure 3).

In this model, when applied to science, distinctions can be made between a representation in a sign (for example, arrows in diagrammatic accounts of force), the interpretation or sense made of this sign (the scientific idea of force), and its referent (the phenomena to which both the interpretation and signifier refer, such as the specific operation of force on objects in the world). This implies that for learners to understand or explain concepts in science, they must use their current cognitive and representational resources to learn new concepts at the same time as they are learning how to represent them. In this way, student representations and their revision can function variously as exploratory tools for initial thinking, scaffolding for building understanding, and records of new thinking and reasoning, depending on the purpose or purposes of the representation.

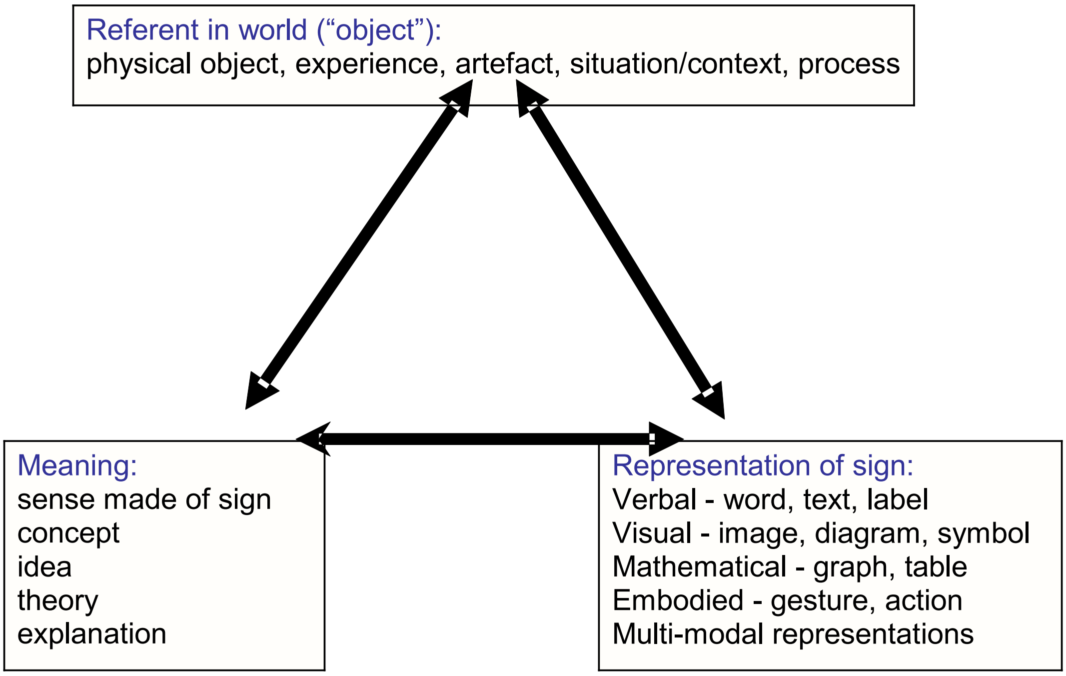

Figure 3: Peirce's triadic model

Apart from this theoretical justification for an explicit focus on representations in learning science, there are strong pedagogical reasons for students to be given opportunities to construct their own representations. Giere and Moffatt (2003) make this point through a comparison with learning long-multiplication in mathematics. They note that many people learn to multiply large numbers that would be difficult to do mentally by using a representational framework of written numbers, symbols and manipulations (Figure 4).

$$\begin{array}{r} 456 \\ \underline{\times\ 789} \\ 4104 \\ 36480 \\ \underline{319200} \end{array}$$

Figure 4: Multiplying two three digit numbers.

This representation functions as a thinking tool or scaffold during the manipulation, and then becomes an artefact of this thinking, shifting from a "live" representation during the process of constructing an answer to a "dormant" representation, unless used for more re-interpretive thinking. A mathematics teacher would not consider students "mathematically competent" in long-multiplication if they had never practised this computation, but had just observed the constructed representation and learnt to recall it by rote. For Giere and Moffatt (2003), the same idea applies in science learning, where students should learn how to use representations as thinking tools for understanding and predicting, rather than memorizing "correct" representations for knowledge display. Supporting this view, diSessa (2004, p 299) asserts that students bring to learning in science some understanding of the need for "conciseness, completeness and precision" in representing ideas, and that "good students manage to learn scientific representations in school partly because they can almost reinvent them for themselves". This implies that students are likely to learn more effectively in science when they see the aptness of representational conventions used in this subject, and also when they recognize the persuasive nature of particular scientific explanations.

Research in Cognitive Science

Recent research in cognitive science (Barsalou, 1999; Grush 2004; Klein, 2006; Schwartz & Heiser, 2006) provides a rich picture of diverse factors that influence effective learning generally, and science in particular. These researchers assert the fundamental role of context, perception, motor actions, identity, feelings, embodiment, analogy, metaphor, and pattern completion in learning. This implies that students are more likely to learn science concepts effectively when they can coordinate perception and actions, such as manipulating a 3D model and noting perceptual links between aspects of the model and the target science concepts and explanations. Grush (2004) claims that the learner's brain is able to engage in very flexible information-processing strategies that link verbal and visual meanings through the interplay of perception, imagination, mental picturing and motor actions. From this new cognitive science perspective, conceptual knowledge is seen more as implicit, perceptual, concrete, and variable across contexts, rather than as primarily propositional, abstract, and decontextualized (Barsalou, 1999).

For Schwartz and Heiser (2006, p. 287)), perception precedes beliefs or knowledge, and therefore can enable or block attention in the "preinterpretative" phase of coming to understand something. They also note that students can visualize and imagine situations and predict outcomes accurately that they cannot verbalize, because perceptual resources and contextual clues provide the bases for this thinking. Klein (2006), Tytler, Peterson and Prain (2006) and others assert that students are more likely to remember appropriate meanings for science experiences when they can also connect them to their personal histories, to meaningful everyday contexts, and to an identity that includes acting scientifically. The implications of this research for representational work are that students need to be supported to (a) map perceptual links between science activities and their 2D and 3D representation, and (b) connect representations with meaningful everyday experiences and interests.

Classroom Research

Researchers in classroom studies where students were guided to construct their own representations of scientific ideas (Greeno & Hall, 1997, Hackling & Prain, 2005; Prain, Waldrip

& Carolan, 2007; Tytler, Peterson & Prain, 2006; diSessa, 2004) have identified various key principles to guide effective planning, implementation, and evaluation of student learning. Consistent with an effective focus on conceptual learning in science generally, the teacher needs to be clear at the topic's planning stage about the key concepts or big ideas students are intended to learn. This conceptual focus provides the basis for the teacher to consider which sequence and range of representations, including both teacher- and student-generated ones, will engage learners, develop understanding, and count as evidence of learning at the topic's end.

This major focus on key concepts in science learning is evident in the national professional learning program, *Primary Connections* (Australian Academy of Science, 2007), where key concepts are emphasized at the start of units of work, and students are expected to develop understanding of these concepts through engaging in guided investigations related to a sequence of representational and re-representational work. Research on the learning outcomes of this program (Hackling, Peers & Prain, 2007; Hackling & Prain, 2005) found that students were more motivated than through past approaches, and that learning performance was also enhanced.

Other classroom studies in this area (Cox, 1999; Greeno & Hall, 1997; Prain, Waldrip & Carolan, 2007; diSessa, 2004; Tytler Peterson & Prain 2006) have noted the importance of teacher and student negotiation of the meanings evident in verbal, visual, mathematical and gestural representations in science. Students benefit from multiple opportunities to explore, engage, elaborate and re-represent ongoing understandings in the same and different representations. Greeno and Hall (1997) argue that forms of representation are useful tools for constructing understanding and for communicating information, and that students need to explore the advantages and limitations of particular representations. However, we would also argue that students need strong guidance in making links between their own representations and authorized ones from the science community.

These studies also indicate that representations in science can serve many different purposes. While these purposes can be considered as conventional and functional for making new meanings in the science community, clearly they can also serve learning purposes for students in the science classroom. In this way, representations can be used as tools for initial, speculative thinking, as in constructing a diagram or model to imagine how a process might work, or find a possible explanation, or see if a verbal explanation makes sense when re-represented in 2D or 3D. They can be used to record precise observations, to identify the distribution of types, to classify examples into categories, to identify and explain key causes, to integrate different ideas, to contextualize the part to the whole, to identify the inner workings of a machine or object, to show key parts, to show a sequence or process in time, to identify the effects of processes, predict outcomes, sort information, clarify ideas, show how a system works, organize findings, explain how parts of a topic are connected, and to work out reasons for various effects.

These studies have also raised the question of how teachers and students might assess the adequacy of a representation. For diSessa (2004), this means that students need to understand that a single representation cannot cover all possible purposes or all aspects of a topic. Therefore they need to learn how to select appropriate representations for addressing particular needs, and be able to judge their effectiveness in achieving particular purposes. He claimed that junior secondary students intuitively have an understanding of the attributes of a good scientific representation, recognizing that it must be clear, unambiguous, give minimal but sufficient information, and be comprehensive for its purpose. By implication, where students are not clear about these criteria or their rationale of producing clear communication, then these aspects need to be taught explicitly.

These studies have also identified a range of benefits from this explicit focus on representational understanding and reasoning. Prain, Waldrip & Carolan (2007) claimed that this approach heightened students' sense of ownership of their work, increased student motivation and creativity, and that teachers reported improved student learning outcomes. Tytler Peterson & Prain 2006) argued that this approach also had the merit of being consistent with science practices of meaning-making in the broader science community.

The IF-SO Framework

Drawing on these theoretical perspectives and recent research in this area, the following framework focuses on key issues in topic planning (see I and F below), and teacher and student roles in learning through refining representations during a topic (S and O).

I: identify key concepts. Teachers need to identify key concepts or big ideas of a topic at the planning stage to anticipate which teacher- and student-constructed representations will engage learners, develop their understanding, and count as evidence of learning.

F: focus on form and function. Teachers need to focus explicitly on the function and form (or parts) of different representations. If a particular representation is crucial to the topic, such as the utilisation of ray diagrams to describe or understand reflection or refraction of light, then this may need to be negotiated at the outset. The conventions in less crucial representations could be covered incidentally or when needed. In working with any new representation students need to learn its function or purpose, and how this function is served by its form or parts. For example in working with graphs, students should be asked to consider why they are used in science, as well as to identify their key parts and their function, such as the purpose of each axis for establishing patterns of data for interpretation. In this way teachers can guide students to learn about a science toolkit of types of representations and their possible purposes as tools for engaging with, reasoning about, explaining and predicting phenomena.

S: sequence. There needs to be a sequence of representational challenges which elicit student ideas, enable them to explore and explain their ideas, extend these ideas to a range of new situations, and allow opportunities to integrate representations meaningfully.

I. **S: student representation.** Students need to have opportunities to re-represent to extend and demonstrate learning. They should be challenged and supported to coordinate representations as a means to express coherent, defensible and flexible understandings. Students need to be active and exploratory in generating, manipulating and refining representations. There needs to be the opportunity for students to express and extend their representational resources.

II. **S: student interest.** Activity sequences need to focus on meaningful learning through taking into account students interests, values and aesthetic preferences, and personal histories.

III. **S: student perceptions.** Activity sequences need to have a strong perceptual context to allow students to use perceptual clues to make connections between aspects of the objects and their representation.

O: Ongoing assessment. Teachers should view representational work by students, including verbal accounts of the topic, as a valuable window into students' thinking and evidence of learning. This assessment can be diagnostic, formative and summative**.**

I. O: opportunity for negotiation. There needs to be opportunities for negotiation between teachers' and students' representations. Students need to be encouraged to make self-assessments of the adequacy of their representations. Are they adequate to their ideas on the topic as well as the features of the object, and to what extent do they achieve the students' representational purposes?

II. **O: On-time.** Timely clarification of parts and purposes of different representations. How do they compare to "authorised" representational conventions as tools for understanding and communication?

IF-SO Framework Implications for an Effective Teaching Style in Science – the "Trialogue"

Roberts (1996) provides useful insights into how different teaching and learning styles in any subject domain affect how and why representations are used, and the capacity for learners to be active participants in learning processes. We draw upon and extend Roberts' approach, and claim that his preferable "Trialogue" teaching style meshes with the IF-SO framework in that both recognize students' prior and developing ways of representing, and reconcile these accounts with new understandings entailed in "authorised" representations. While each of the following comparative styles may represent extremes of practice, analogous with Fleer and Hardy's (2001) categories of transmissive and discovery approaches, we claim that they are recognizable teaching orientations to topics in some science classrooms.

Style One: Teacher Imposition

In this style, students are not provided with opportunities to construct and judge their representations by comparison with peer efforts, but are expected to learn authorized accounts from text books or the teacher. In this style, the teacher seeks to impose "accepted wisdom" about the topic by modelling or demonstrating understandings through guided experiences, reported observations, and control of the representations and explanations, as indicated by the arrows between teacher and domain (Figure 4). The "legitimacy" of students' understanding through their need to link and resolve prior representations with "authorised" ones is minimized, other than their right to seek teacher clarification of understanding, as suggested by the double-headed arrow between teacher and student (Figure 4).

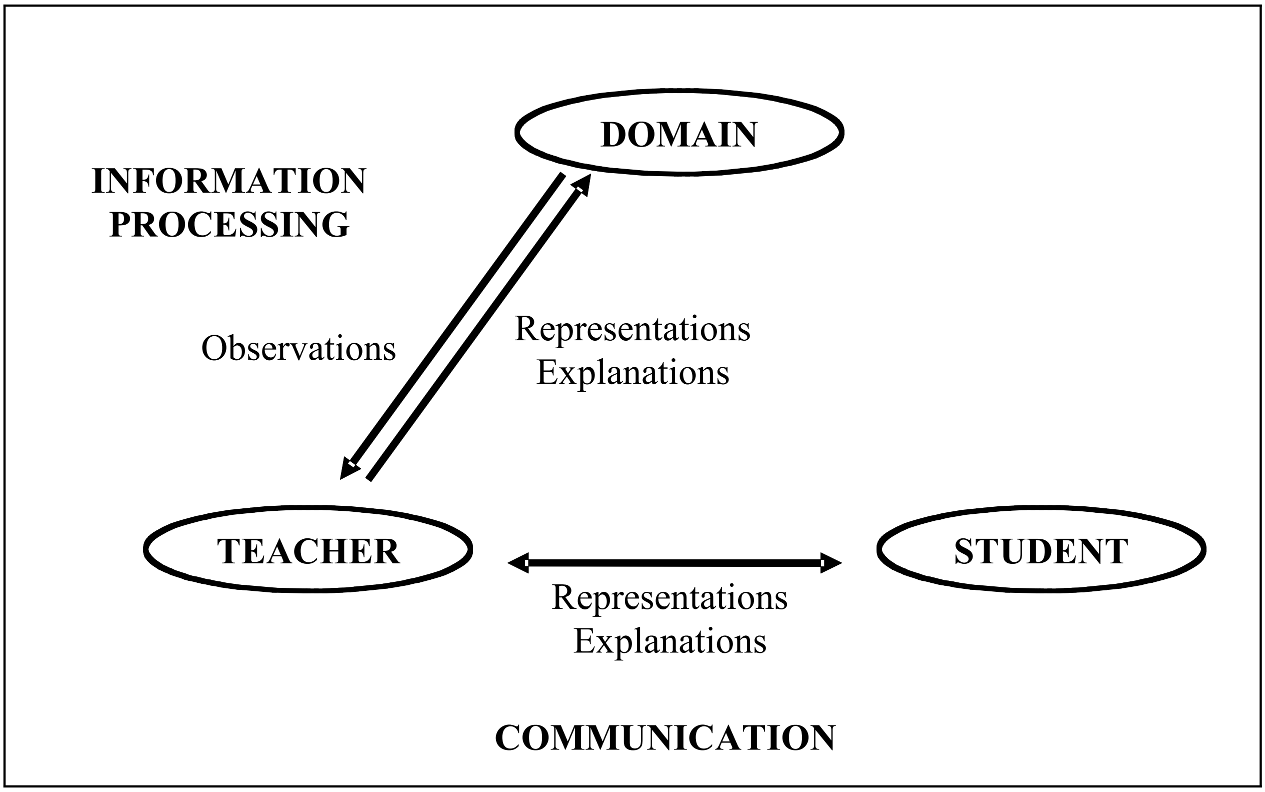

Figure 4: Teacher Imposition

Style Two: Teacher Abdication
In this style the teacher's fundamental role as coach and advocate for the "accepted wisdom" of the domain is abandoned. Students are left to their own devices to interpret or construct representations to explain their observations of the domain, indicated by the arrows between student and domain (see Figure 5). This perspective assumes students have the metacognitive ability to recognise why authorized representations have been accepted as more compelling ways to establish knowledge in the domain, and that students might "discover" the adequacy of these accounts without strong guidance by the teacher.

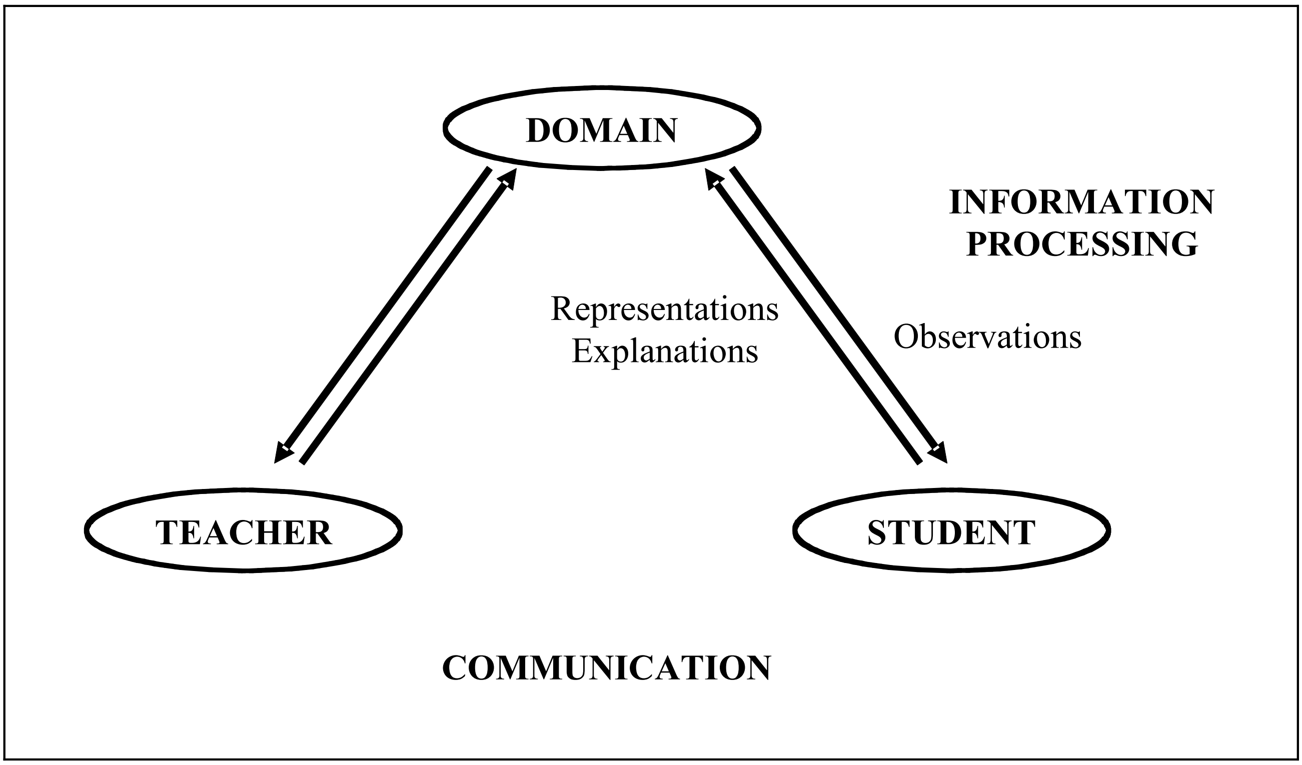

Figure 5: Teacher Abdication

Style Three: Teacher as Domain Novice

Students are again left to interpret or construct representations to explain their understandings of the domain. However, because the teacher is unfamiliar with, or unable to understand, its representations, their conventions or explanations, he or she can provide little guidance on, or assessment of, student understanding or use of representations. The teacher may question students about their understandings, as indicated in the double arrow head between teacher and student (Figure 6), but has insufficient domain knowledge to coach students to link and resolve their representations with "authorised" ones.

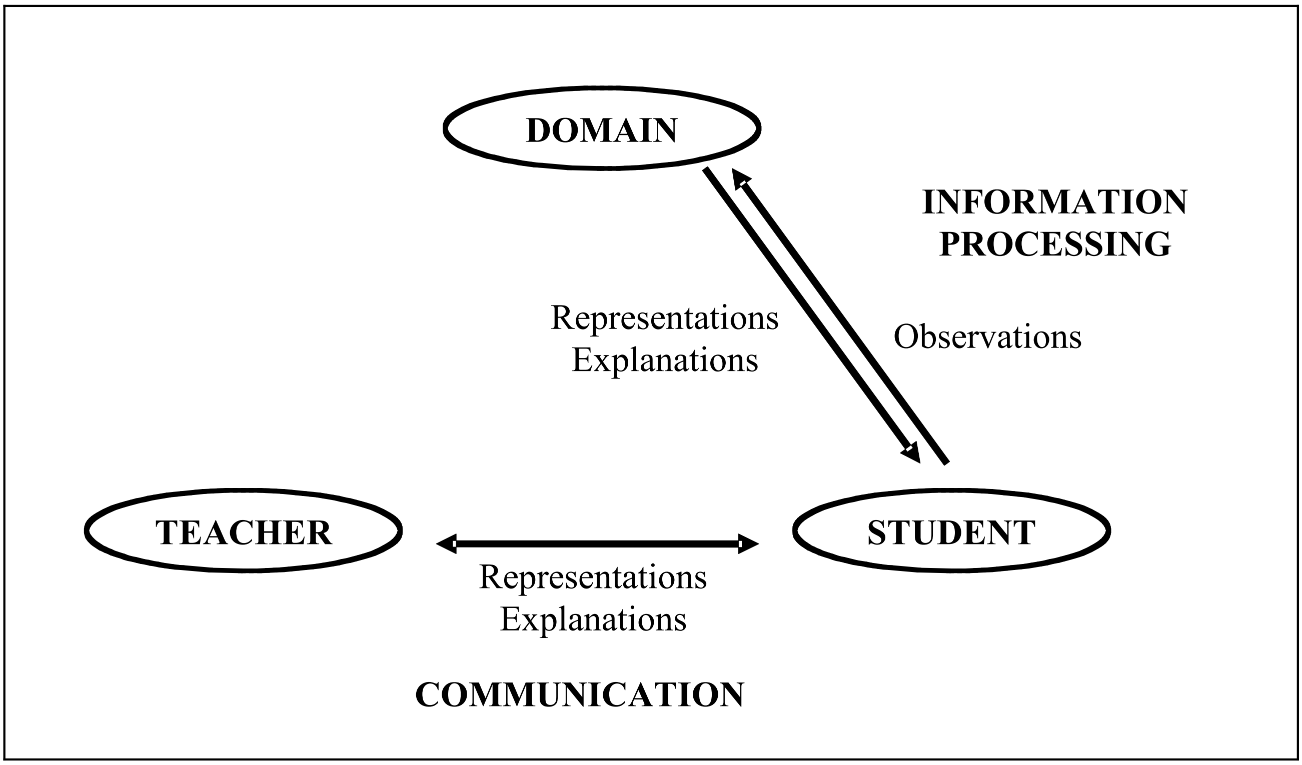

Figure 6: Teacher as domain novice

Style Four: Teacher in Trialogue

Roberts' (1996, p. 423) "trialogue" proposes a three-way reciprocal linkage between teacher, student and domain. In this model, guided by some suitable scaffolding, students are encouraged to generate their own representations to explain observations and predict future outcomes. They can then compare and reconcile these representations with those of their peers, and with those of their teacher, or those presented by their teacher as current within the science community. The teacher then acts as coach and negotiator of the meanings of these representations and their refinement through a range of representational tasks. The arrow from teacher to student indicates the accepted wisdom of representations, as communicated by the teacher, while the reverse arrow indicates the students' prior or developing representations of the domain (Figure 7).

The trialogic style affirms the students' needs to generate their own explanations and compare these accounts to others, making the material meaningful to themselves and to others. This style both recognizes the need for active learner participation, and teacher responsibility to coach students about the reasons behind the acceptance of representational modes, forms, conventions and interpretation. As students move into the "community of science" it is crucial for them to be cognisant and conversant in the languages and practices of this subject. Whilst established conventions and interpretations are no longer negotiated, it is also important for students to recognize that they once were, and this is still the case for some new procedures and findings. This style makes no assumption of students' metacognitive ability to recognize spontaneously pertinent features of the representations and their meaning, or the overall applications and limitations of a representation (as well as any of the representation's advantages over students' own personal representations), without some teacher guidance. Instead, the teacher guides the students to recognize each representation's key features and, in a 'precious metacognitive lesson' (Roberts, 1996, p. 427), recognize how these features act as knowledge "justifiers" or "definers" in the domain.

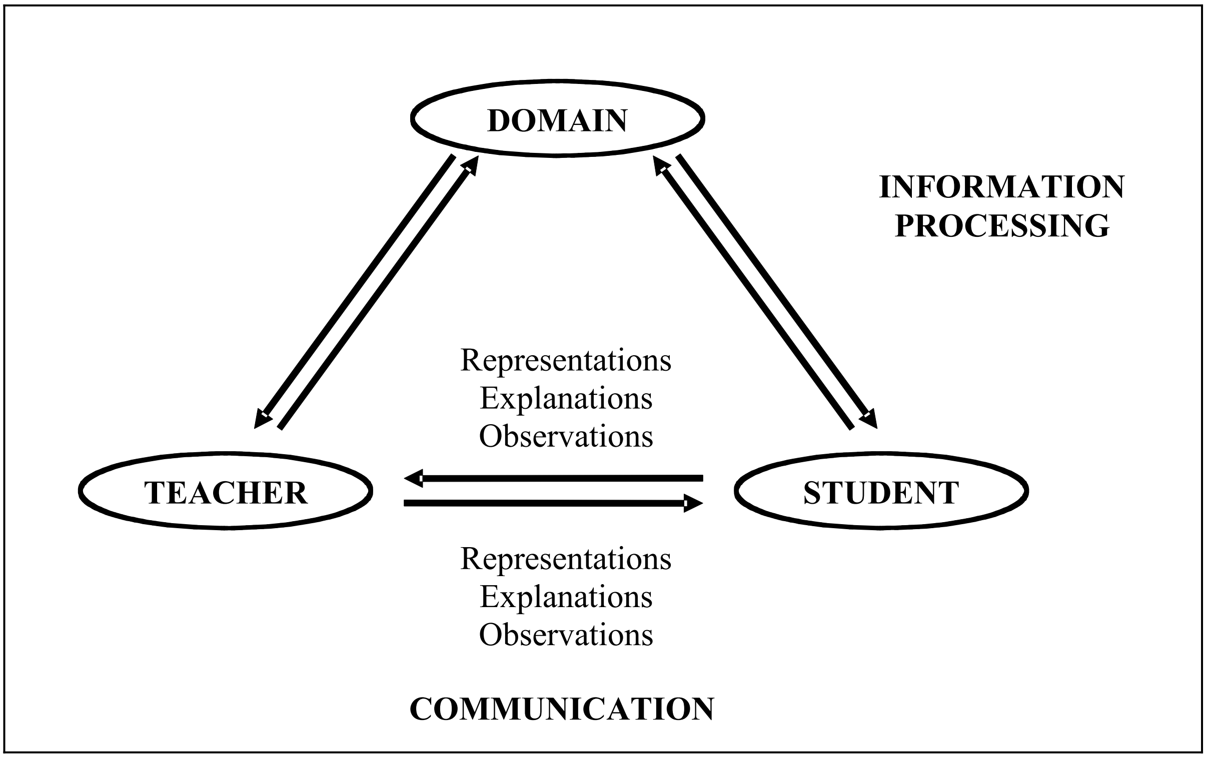

Figure 7: Teacher in Trialogue

The Trialogue Style of Teaching using the IF-SO Framework

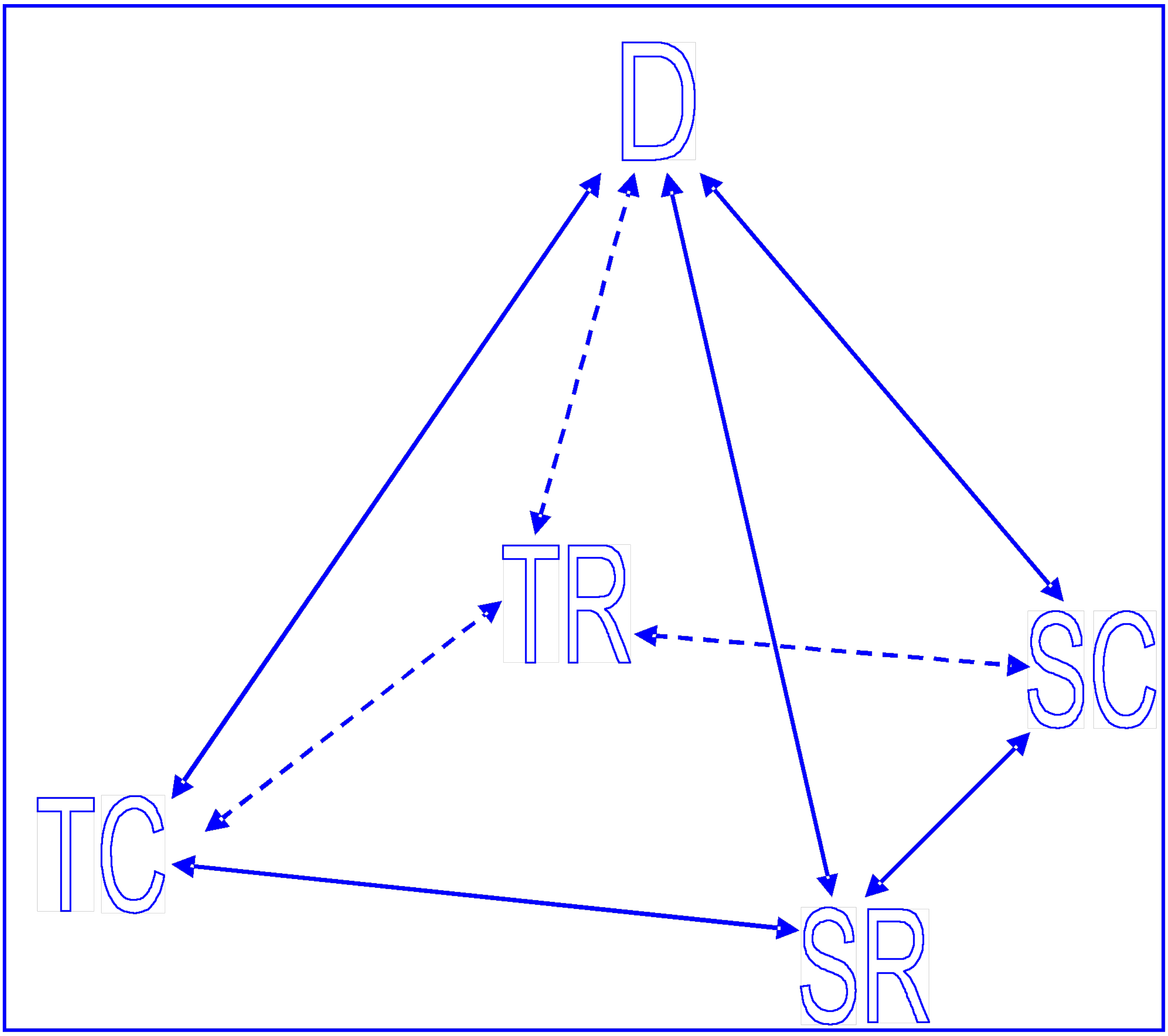

Figure 8: Triadic Pedagogical Model

This IF-SO framework can be understood as combining Peirce's (1931-58) account of the three components of meaning-making (Figure 3) with Roberts' (1996) model of pedagogy (Figure 7), and is represented as a set of interlocking triads (Figure 8). From this perspective, teaching and learning in science entails various triads incorporating the domain (D), teacher conceptions (TC), teacher representations (TR), student conceptions (SC), and student representations (SR), that are mutually supportive (Figure 8). At all stages in the learning process, the teacher must rely on interpreting students' representations as evidence of their understanding.

In the planning phase triad (IF), the teacher chooses the key concepts (TC), the aspects of the domain (D), such as physical objects, experiences, artefacts, situation/context or processes, that will be the focus of the unit, and the types and sequence of representations to use to engage students and develop their understanding (TR). The teacher also needs to consider the purpose of any student representational work.

In the planning phase of a unit on "Forces" the choice of ideas, their exemplar references to be focussed on from the domain and the ways of representing these will depend on the class level. For a junior class the teacher might identify the key idea as being "forces are pushes or pulls", the focus being simple directly (physically) perceptible examples of force involving contact such as pulling a drawer or pushing a door, and student convergence on the use of simple symbols (perhaps arrows) functioning to represent force direction and magnitude. At this level, the symbol (arrow) directions could be approximate, and magnitude related to thickness, shape or colour of symbol rather than their length, without really diminishing fundamental learning of the key ideas. In order to communicate their ideas, however, students will need to negotiate and define their conventions to allow common interpretation, importantly reflecting practices within the broader science community. In more advanced classes students need to develop a more abstract view of forces, such as an understanding of how forces can balance out. In this case, following accepted conventions about the use of arrows to represent force as vectors may best facilitate communication and learning of the key ideas.

Thus in the sequence of classroom lessons (S and O), different triadic emphases might occur, depending on stages in the topic and student knowledge, interests, and needs. Where key concepts are highly abstract, then students may need guidance in learning how to use accepted conventions to explore relevant ideas. This suggests the value of focusing on the triad of the Domain, Teacher Representations and Student Conceptions (D, TR, SC). Where students can engage initially or further with the topic because of their understanding, the teacher might facilitate student constructions, focusing on the triad of domain, student representations, and student conceptions (D, SR, SC). As stated in the IF-SO framework, we believe it is crucial that students have opportunities to create their own representations of the domain to motivate them, develop representational competence, and learn science. The teacher and class then need to assesses the convergence or compatibility of these representations with authorized ones, using a different triad (TC, D, SR). The success of this work then frames directions for subsequent lessons, establishing if there is a need for explicit teacher-guided negotiation of students' current representational meanings.

While we have not focused explicitly on reasoning in science in this paper, the proposed approach also provides ways to link representational work with developing convincing explanations. Negotiating representational meaning provides many opportunities for students to consider possible claims, evidence, and reasons in developing scientific accounts of the physical world. For example, students can use representations such as organized data in graphs to identify patterns in data distribution. They can also translate ideas from one type of representation to another, thus shifting their mode of reasoning as they re-organize their understanding to take into account visual, spatial and verbal aspects of topics. As students develop a representation, the teacher and/or students can direct attention to inconsistencies of interpretation, and thus provide further opportunities for reasoning. Constructing representations can also enable students to keep track of their progress in problem-solving in a topic, can refine and clarify first impressions, and can promote the pleasure of recognition of understanding when students see that their representation makes a clear and convincing case.

References

Australian Academy of Science (2007). *Primary Connections.* www.science.org.au/primaryconnections. Accessed 15.3.2007.

Barsalou, L.W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*, 577-609.

Cox, R. (1999). Representation construction, externalized cognition and individual differences. *Learning and Instruction, 9*, 343-363.

Fleer, M., & Hardy, T. (2001). *Science for Children. (2nd Ed)*. Frenchs Forest, Australia: Pearson Education Australia.

Giere, R. & Moffatt, B. (2003). Distributed cognition: Where the cognitive and the social merge. *Social Studies of Science 33*, 301-310.

Greeno, J.G., & Hall, R.P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan, 78* (5), 361-368.

Grush, R. (2004). The emulation theory of representation: motor control, imagery, and perception. *Behavioral and Brain Sciences* 27:377-442.

Hackling, M. & Prain. V. (2005). *Primary Connections. Stage 2 trial: Research Report*. Australian Academy of Science.

Hackling, M, Peers, S. & Prain, V. (2007). Primary Connections: Reforming science teaching in Australian primary Schools. *Teaching Science 55* (3), 12-17.

Lemke, J. L. (2003). Mathematics in the Middle: Measure, Picture, Gesture, Sign, and

Word. In M. Anderson, A. Sàenz-Ludlow, S. Zellweger & V.V. Cifarelli (Eds.), *Educational Perspectives on Mathematics as Semiosis: From Thinking to Interpreting to Knowing* (pp. 215-234). Ottawa: Legas Publishing.

Peirce, C. S. (1931-58). *Collected Papers of Charles Sanders Peirce*. 8 Volumes (Eds. Charles Hartshorne, Paul Weiss & Arthur W Burks, Vols 1-6), (Ed., Arthur W. Burks, vols 7-8). Cambridge, MA: Harvard University Press

Prain, V., Waldrip, B., & Carolan, J. (2007). Representational opportunities and learning in science. Paper presented at the Australasian Science Education Research Association Conference, Fremantle, July 12-14, 2007.

Roberts, D. (1996). Epistemic authority for teacher knowledge: The potential role of teacher communities: A response to Robert Orton. *Curriculum Inquiry 26* (4), 417-431.

diSessa, A. (2004) Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction 22* (3), 293-331.

Schwartz, D & Heiser, J. (2006) Spatial representations and imagery in learning. In R,K. Sawyer (Ed) *The Cambridge Handbook of the Learning Sciences*. Cambridge University Press, 283-298.

Tytler, R., Peterson, S., & Prain. V. (2006). Picturing evaporation: Learning science literacy through a particle representation. *Teaching Science, 52* (1), 12-17.

Tytler, R., Prain. V, & Peterson, S. (2007) Representational issues in students learning about evaporation. *Research in Science Education 37* (3), 313-331.

Waldrip, B., Prain, V., & Carolan, J. (2006) Learning Junior Secondary Science Through Multi-Modal Representation, *Electronic Journal of Science Education 11 (1), 86-105.*

Waldrip, B. & Prain, V. (2006) Changing representations to learn primary science concepts. *Teaching Science 54* (4), 17-21.