Chapter 1
The Centrality of Models for Knowledge Claims in Science Education

> Our knowledge of others, in short, is essentially no different from our knowledge of the world. Because it is the result of our own perceiving and conceiving, it cannot be a true representation of independently existing entities; but insofar as we can use it as a basis for further acting and thinking it constitutes a viable model of these very special elements of our experiential world. (Glasersfeld, 1988, p. 6)

Science education is an active field of research and scholarship (Fensham, 2004), concerned with the teaching and learning of science. Although a broad field of research, a key focus has been on learners' knowledge and understanding of aspects of science and how this changes – that is, science learning. Such enquiry has been undertaken with a view to informing better pedagogy, to support teachers in their role in facilitating learning.

Studying learning from a science education frame clearly has significant potential to overlap studies of learning undertaken as part of psychology and often carried out in science contexts. Indeed there need be no absolute distinction here, and certainly some published studies can contribute to both disciplines: however, psychological research is likely to be motivated primarily by general questions about the nature of human learning, with science learning providing contexts seen as suitable for particular studies, whereas work undertaken in science education will tend be undertaken with a view to being directly relevant to informing more effective science teaching.

Research into what students 'think', 'know' and 'understand' about science – and as will be discussed these words are often taken for granted but deserving careful specification when used as technical terms in a field of scholarship – serves a number of purposes.

From the perspective of effectiveness, if science teaching is about facilitating student learning, then we need to find out whether students have learnt. For that we need to find out what students know or understand, both before and after teaching, to judge if there has been any learning. In principle this could be down to individual teachers using classroom assessment. However, in planning curriculum (e.g. at a National level) it is important to have a fairly good overview of what students generally know and understand and are likely to be able to learn next, at particular ages.

K.S. Taber, *Modelling Learners and Learning in Science Education: Developing Representations of Concepts, Conceptual Structure and Conceptual Change to Inform Teaching and Research*, DOI 10.1007/978-94-007-7648-7_1,

Much thinking about such issues within science education has been informed by a constructivist perspective (Bodner, 1986; Gilbert & Watts, 1983; Glasersfeld, 1989), which can be characterised as appreciating how future learning is highly contingent upon the current state of an individual's knowledge/understanding (Taber, 2009b). This will be considered in more depth later in the book, but for the moment it is important to note that as a result of the widespread influence of a constructivist perspective, *a good deal of research in science education has made claims about what learners know and understand or how their knowledge and understanding have changed* – that is, claims about learning. Some examples of such claims are considered below.

The central argument of this book is that these knowledge claims are *inevitably based on models*, and so the claims made in research reports can only be fully appreciated by readers who both recognise the models for what they are and understand something of the modelling processes used to derive them. The motivation for this book derives from concerns that this is not always made explicit in research reports nor fully appreciated by those who use them. This lack of appreciation of the status or research findings and the processes that produce them undermines the potential of the research to inform more effective classroom work.

Some Examples of Knowledge Claims Made in Studies

It is useful to provide readers with a few examples from the literature of what I mean by 'knowledge claims' in studies of student thinking, understanding and learning in science. I have selected a range of examples that in this form are necessarily stripped of their context within the original authors' accounts to illustrate something of *the range* of kinds of claims made in this area of research (see Table 1.1). Anyone familiar with the literature in this area will recognise these types of knowledge claims as being very common in science education research. I have italicised some key terms to highlight the kinds of entities being referred to in these claims. Clearly for a reader of a study to fully understand its conclusions, there needs to be a 'shared' (as far as this may be possible) understanding of what is meant by these terms in the contexts of these claims.

Most of the examples in Table 1.1 refers to what later in the book will be described as the mental register: terms such as ideas, thinking and understanding. Some of the terms used are less familiar from everyday life (p-prim) and so are likely to strike the reader as technical terms. However, when research results make claims about learners' ideas or beliefs, then these words ('ideas', 'beliefs', 'understanding', etc.) are being used as technical terms, even though they are everyday words and readers may therefore take for granted a shared meaning for such terms with the report authors. This book argues that it is unwise to assume that we do all share common understandings of such terms and seeks to explore how such words should be understood when recognised as technical terms in science education research.

Table 1.1 Examples of knowledge claims in science education research

1. 'about one-third of the pupils at the compulsory school *have little understanding* of chemical change' (Ahtee & Varjola, 1998, p. 310)
2. 'there is *a common core* to the pupils' explanations and predictions in such widely differing areas as temperature and heat, electricity, optics and mechanics' (Andersson, 1986, p. 155)
3. 'A large percentage of teachers (76 %) and students (46 %) *believe* that, for the same concentration the pH of acetic acid will be less than or equal to that of hydrochloric acid solution in water' (Banerjee, 1991, p. 491)
4. Data suggest that many students begin post-16 studies with a wide range of *misunderstandings* about chemical reactions. However, students' *understanding improves* steadily as the course progresses (Barker & Millar, 1999, p. 645)
5. 'Everyone recognizes the phenomenon that earthly motion essentially always dies away… dying away is often taken intuitively as a *primitive*. This p-prim is essentially the stipulation that a certain pattern of amplitude (gradual diminuendo) is natural for a particular class of amplitudes (actions by inanimate objects that are not subject to continuous influence). Novice adults often treat dying away as a relative primitive. That is, they will often be satisfied with an explanation that does not have any particular cause for the dying away'. (diSessa, 1993, p. 133)
6. '…many people have striking *misconceptions* about the motion of objects in apparently simple circumstances. The misconceptions appear to be grounded in a systematic, *intuitive theory* of motion that is inconsistent with fundamental principles of Newtonian mechanics'. (McCloskey, 1983, p. 114)
7. 'Students' *conceptual understanding* of photosynthesis and respiration in plants was *measured* … The conceptual change instruction, which explicitly dealt with students' *misconceptions*, produced significantly greater achievement in *understanding* of photosynthesis and respiration in plant *concepts*'. (Yenilmez & Tekkaya, 2006, p. 81)
8. 'for some participants personal *beliefs* (including religious beliefs) appear to override their scientific training and the norms of their profession; for others personal beliefs are paramount; and, for some personal beliefs and *scientific thinking* are compartmentalized'. (Coll, Lay, & Taylor, 2008, p. 211)
9. '[Sister Gertrude Hennessey] pursued a structured approach to science instruction that made students' *thinking* visible and therefore accessible to her observation'. (Lehrer & Schauble, 2006, p. 167)
10. '…pre-Galilean *ideas* about force and movement are not only prevalent among school children, but also in certain cases do persist even after years of formal exposure to physics teaching. There is also evidence to suggest that, at least when projectile motion (vertical or composite) is considered, the *conceptions* are closer to the mediaeval impetus theories than to the older Aristotelian conceptions'. (Gilbert & Zylbersztajn, 1985, p. 117)

Knowledge Claims in Research

Science, in the broad sense of the word, is about the furthering of human knowledge, that is, *public* knowledge. In philosophy, 'knowledge' is sometimes defined as justified, true belief (Matthews, 2002). By such a definition, we can only consider something as knowledge if it is true, *and* we have had it demonstrated as being true. This is considered further later in the book, in the context of what we mean by a learner's knowledge; see Part III. Philosophers of science have argued that science is not able to produce any general abstract knowledge which can logically be demonstrated to be true in this sense, that is, absolutely true for all time. Science deals with conjectural knowledge, which – to be accepted into the canon of scientific knowledge – must have strongly supported grounds *but* remains provisional, at least in principle. Scientific knowledge is fallible, and the scientific attitude is to always consider that in principle even the best established ideas are open to challenge and should be revisited if strong evidence comes to light that undermines their authority (Popper, 1934/1959).

The process by which knowledge becomes widely accepted in science is somewhat organic but starts with the presentation of a new knowledge claim, and the evidence for its support, for peer review within the scientific community, that is, the submission of a report of research to a recognised peer-reviewed scientific journal. The publication of research reports in such journals is used as a criterion that the research is considered to be sound, and so that the knowledge claims made are well supported. This does not mean that the conclusions are accepted as 'proven' knowledge but, rather that the claims are seen to have sufficient support to deserve to be taken seriously. The processes by which the claims made in individual papers are variously challenged, elaborated, ignored, forgotten, built upon or come to be seen as seminal are certainly important but have been somewhat open to dispute in different accounts of the scientific enterprise. Suffice here to say that *an accumulation of evidence from programmes of research* establishes major new ideas as accepted components of scientific knowledge, even when it seems clear that a particular 'seminal' study plays a major role in stimulating a particular research direction (Lakatos, 1970).

Locating This Work Within a Research Programme

I have elsewhere (Taber, 2006a) considered how research into student understanding and learning of science may be understood as a scientific research programme (SRP), in the sense proposed by the philosopher of science Imre Lakatos (1970). In particular, I have argued that conceptualising research associated with the 'alternative conceptions movement' or 'constructivism in science education' as a research programme (RP) is necessary both as (a) a basis for clarification of a diffuse and diverse body of work to defend this area of work from its critics (Taber, 2006c) and (b) to identify the 'progressive' elements which should direct continued research (Taber, 2009b). That is, the process of characterising an RP is important both in 'external' terms (in establishing its identity, location in a field and relationship with other RP in that field) and in 'internal' terms (because a key feature of a RP is that it offers heuristic guidance to those working within the programme).

The Constructivist Research Programme

In that previous work I argued for (1) the existence of this RP as an identifiable component of the field of science education (something that had been broadly accepted), (2) a particular characterisation of the RP (somewhat different from some earlier characterisations) and, most importantly, (3) its status as a *scientific* RP (SRP) in the sense in which Lakatos (1970) sets out demarcation criteria – that is, that the RP was theoretically and empirically 'progressive'. Each of these points is open to challenge, and in the latter case there could be an argument for considering the current status of the RP as 'somewhat' progressive as developments in the area in the past decade have not been as frequent or as coherent as might be expected in an active international programme of enquiry. Nonetheless I consider the general case to be very strong, and here I largely assume the existence of the RP rather than conceptualise this area of work as a number of discrete RP or a disparate set of researchers/research groups working largely independently.

In my previous work there was emphasis on how the identification of a common core of ontological and epistemological key commitments – the programme's hard core in Lakatos's terms – provides a basis for demarcation: for judging which work falls within the tradition of a particular RP. I suggested (Taber, 2009b, p. 123), based on analysis of much-cited key studies, that the hard-core commitments of the research programme into the contingent nature of learning in science ('constructivism') are:

- Premise 1. Learning science is an active process of constructing personal knowledge.
- Premise 2. Learners come to science learning with existing ideas about many natural phenomena.
- Premise 3. The learner's existing ideas have consequences for the learning of science.
- Premise 4. It is possible to teach science more effectively if account is taken of the learner's existing ideas.
- Premise 5. Knowledge is represented in the brain as a conceptual structure.
- Premise 6. Learners' conceptual structures exhibit both commonalities and idiosyncratic features.
- Premise 7. It is possible to meaningfully model learners' conceptual structures.

The assumptions are carried into the present study. It is important to note that although this particular account of the essence of constructivism in science education is my own formulation, all of these principles are long established in the science education literature (cf. Sjøberg, 2010). I have simply drawn out, reformulated and re-presented the key ideas proposed, modified and largely accepted by many other researchers. I refer readers interested in the original sources of these ideas to previous work (Taber, 2006a, 2009b) and here look to build upon and develop aspects of that earlier analysis. The assumption of an SRP provides a focus for the justification for the present work and offers a coherent context or range of application for the ideas discussed here. However, the arguments made in this volume do not *depend* upon accepting the notion of the SRP in science education: the issues explored here are fundamental to a wide range of research studies, however those studies are collectively conceptualised.

The research context for the present volume is shown in Fig. 1.1. A key feature of this representation is that the relationship between learning and thinking is two

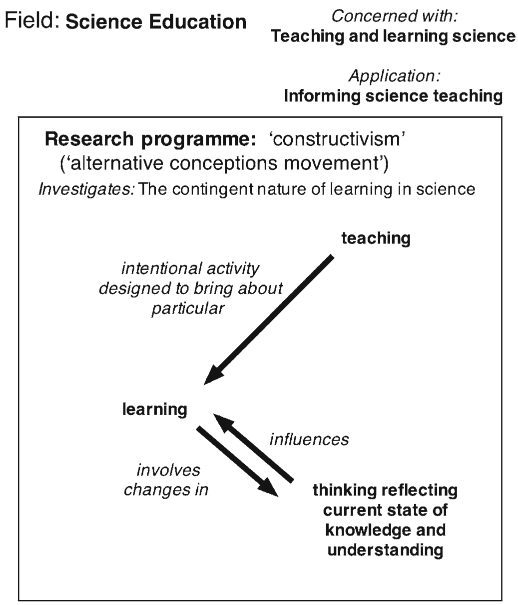

Fig. 1.1 The research context of the present study

way: that is, not only can learning facilitate changes in the individual's thinking but thinking (which depends upon the current state of the learner's knowledge) influences learning.

The reader should note therefore that the arrow from 'teaching' to 'learning' is labelled in terms of *the intentions* informing teaching. An individual will learn from interactions with those around them, whether they are conscious of having a teaching role or not (Vygotsky, 1978): teaching is the term we use to describe behaviour which is deliberately undertaken to facilitate learning, and educational research has this type of behaviour as a key focus (Pring, 2000). There is no direct causal relationship between a teacher's intentions and the student's learning: teaching *behaviour* is likely to have consequences, but not always the intended or anticipated ones – as all experienced teachers will likely acknowledge. For the constructivist, teaching can certainly facilitate learning, but not in an unmediated way.

Progressing the Research Programme

The analysis of this area of work in terms of a RP serves the heuristic role of helping identify priorities for research – drawing upon what Lakatos called the positive heuristic of a RP (Taber, 2009b) – and the present volume follows up on one of the key areas that my earlier analysis suggested could impede progress in this area of work. It was argued in my previous work that the premises of the RP lead to broad research questions (this is what Lakatos, 1970, referred to as the positive heuristic of a programme: the way it suggests the direction for research). In particular, the premise 'It is possible to meaningfully model learners' conceptual structures' leads us to ask 'What are the most appropriate models and representations?' (Taber, 2006a).

That is, work in the constructivist tradition in science education assumes that it is possible to make meaningful claims about the knowledge in learners' minds – its extent, organisation, match to target knowledge and so forth – as in the examples quoted above (in Table 1.1). Yet, in a field which notoriously has failed to develop an agreed terminological canon (Abimbola, 1988), there is little agreement on how best to understand and describe the nature of personal knowledge – as again is illustrated in the range of the examples quoted.

The focus in the present volume then is on the nature of studies which contribute to the RP and, in particular, the way that key concepts are used and how this effects how data (e.g. student utterances, such as replies to a teacher's or researcher's questions) are understood, and results are conceptualised (e.g. being considered as alternative frameworks, mental models and proportions of samples reported to have acquired concepts or to hold particular conceptions) and reported. These are central issues in interpreting research reports within the RP.

It was clear from work reviewed previously (Taber, 2009b) that even within what could be considered the 'same' overall programme, there was not only limited common agreement on the meanings given to key terms but often also a lack of clarity in the precise nature of the phenomena discussed and the theoretical entities inferred or posited. Such issues clearly impede effective communication *between* researchers and *with* other 'users' of research, such as teachers and curriculum planners, and undermine the smooth development of a research programme.

Put succinctly: *in many research papers it may not be entirely clear to readers what the descriptors used in knowledge claims are really understood to refer to*. It is that concern which provides strong motivation for the present book.

Assumptions Informing the Research Process May Not Be Explicit

It will be argued in this book that to some extent the confusion, ambiguity and vagueness that can be found in the research literature in this field can be understood in terms of

(a) the uncertain nature of
(b) the inaccessibility to direct observation of

the objects of research.

Referring back to Fig. 1.1, it is clear that the central foci of research cannot be readily observed. I have suggested (Taber, 2009b) that learning is best understood in terms of a change in the behavioural *repertoire* of an individual, as all that can be observed is the behaviours of the individual that are produced in particular contexts. What can be observed, and so recorded to form research data, are such behaviours as utterances (what the individual says), inscriptions (such as written answers to questions) and 'body language' such as nods, shrugs and various gestures. The same is true in regard to the teacher seeking information to support effective teaching. The teacher may use diagnostic probes to test background knowledge or ask questions in class to check on student understanding but then has to interpret the learners' behaviours – their written or spoken responses – to infer what they currently know and understand. Thinking (the focus of Chap. 7) cannot be observed directly, nor can 'understanding' (the focus of Chap. 6) or 'knowledge' (considered in Part III). It will be suggested in Chap. 2 on what I label the 'mental register' that these common-sense notions of knowledge and understanding are actually quite problematic in a research context.

It should be noted, however, that these references to *the central significance of behaviour* to the research field certainly do not suggest adherence to a *behaviourist* position (J. B. Watson, 1967). The behaviourist (or behaviorist) perspective considered that research in psychology should not concern itself with non-observables, and, for example, Watson not only argued that the notion of consciousness was neither definable nor usable but claimed the terms was simply an alternative to 'soul' and so had inherent religious (and so superstitious) connotations (J. B. Watson, 1924/1998). The stance taken in the present book shares with the behaviourists a concern that not-directly-observable foci such as thinking, understanding, knowledge and the various descriptors for aspects of learners' conceptual structures are inherently problematic constructs for research; however, I certainly do not share the behaviourists' response to this problem in excluding these constructs from consideration (J. B. Watson, 1924/1998). Rather, I certainly welcome how 'information processing and constructivist models of learning have supplanted behaviourism as the dominant theory. They encompass a much wider set of variables, including content, perception of context, abilities, prior knowledge, attitudes, and purposes' (White, 1998, p. 61). Many variables of interest are *not directly observable* and so need to be inferred indirectly, but this does not mean we must exclude 'mental' terms such as understanding from our academic and professional discourse. Rather we have to keep in mind that such terms are often used without careful definition, and that they refer to what we infer rather than what we can directly observe.

Arguably *even teaching cannot readily be observed directly*. Behaviours of teachers in teaching contexts can certainly be observed, but to the extent that teaching involves *intentional* acts directed at bringing about learning, observed behaviour needs to be interpreted before it can be classed as teaching. So a stare which is a behaviour which can be observed could be intended as a behavioural prompt to a particular student, or could be a gestural illustration or analogy to make some teaching point, or could just be an unintentional by-product when the teacher has paused for thought – or has just noticed a drastic change in a student's hairstyle. Similarly with verbal behaviour, a question about whether anyone in the class watched a certain television programme the previous evening could be a lack of engagement in the lesson, an attempt to develop rapport to support a teaching relationship or the opening move in drawing a teaching analogy from something in shared experience. The present volume does not focus on teaching *behaviours* in any detail, but the

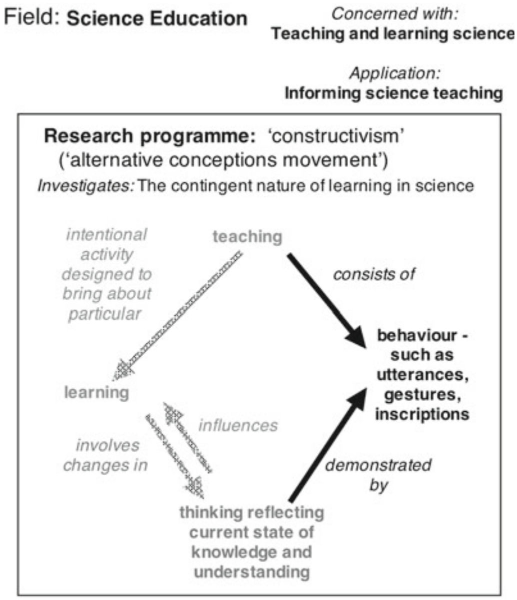

Fig. 1.2 Observable correlates of teaching and learning

fundamental problems for research in exploring learner thinking discussed here have their counterparts in research looking at *teacher thinking*.

This situation is reflected in Fig. 1.2, where within the RP the only available direct observables are indirect evidence of the key concerns of researchers. Arguably, then, teaching and learning are not phenomena in a strict sense: classroom phenomena such as talk have to be interpreted in terms of theoretical notions relating to teaching and learning.

Alternative conceptions, mental models, conceptual ecologies (discussed later in the book) and the various other notions introduced to discuss this area of research are certainly *not* phenomena in the usual sense of that which can be observed and needs to be explained. What is to be explained is what students say and write etc. (in normal classroom situations, in formal assessment and in research investigations), and notions of student knowledge and understanding, etc. are theoretical constructs that have been used to help develop explanatory accounts for patterns in *those* phenomena.

So a classroom teacher may observe learner behaviour when asked, for example, to explain the significance of the periodic table. As a result of considering the learner response, the teacher may then undertake certain teaching behaviours intended to facilitate a different response to the question on a future occasion. Some time later the teacher may ask the learner the same question, and again listen to the response, and so evaluate whether teaching has had the desired effect. In making decisions about what and how to teach, and judgements about whether the teaching has been successful, the teacher will be conceptualising the learner responses in terms of a mental model of the learner knowing and understanding certain things and having learnt (or not) as a result of the teaching intervention. The teacher's thinking is in terms of the learners' knowledge, understanding and learning – but all the teacher actually experiences is what the learner says when asked questions, and so the teacher is working with a theoretical interpretation of this 'data' to infer mental properties and events that can only be inferred.

The same limitations apply to researchers, with the important caveat that the teacher usually has ongoing opportunities to test and correct their interpretations of learner behaviour as they interact with the same learners over extensive periods. The researcher, however, often has a much more limited window to collect data from any particular learner and so limited opportunities to test their interpretation of that data. Moreover, whilst the teacher is involved in a process of modelling the mental states of learners, the purpose of the modelling is to inform practice within the present teaching context, whereas the researcher needs to produce interpretations that have relevance to (even if they cannot be said to directly apply to) other teaching and learning contexts: that is, researchers are charged with producing generalisable theoretical knowledge, where teachers need to work with fit-for-purpose understandings of their own classrooms. As the researcher usually lacks the myriad opportunities for self-correction of interpretations of learner behaviour available in teaching and is expected to produce a public account of work which is theorised in formal terms suitable for communication to the wider science education community, it becomes much more important that the researcher is aware of, and clear about, how they interpret and conceptualise their data.

The Centrality of Models in Research

Given these very real impediments to research, it becomes important for the researcher, and readers of the research, to be very clear about *the indirect nature* of much of the research and *the status of the various entities* discussed. In particular, it should be recognised, and made explicit, that the descriptions researchers offer of aspects of learners' knowledge structures are inevitably of the form *of models*. Research reports that fail to make this clear can be misleading, and this can have unfortunate consequences. Firstly such reports can give false impressions to practitioners wishing to learn from and apply the findings of research in educational practice. Secondly, such imprecision means that knowledge claims in research reports can be readily misunderstood by other researchers – contributing to some of the less helpful examples of claim and counterclaim in the research literature (Taber, 2009b). When teachers not intimately involved in research processes themselves are users of such reports, there is a considerable scope for the overliteral reading of reports (i.e. reifying terms carelessly used as nouns and assigning inappropriate status to conjectural, 'first-approximation' and overgeneralised notions).

It is unlikely researchers commonly deliberately mislead their readers in this regard. Rather these flaws in many research reports are likely to be due to a combination of the following: (a) deliberate attempts to keep reports clear and concise (an admirable enough aim in itself), (b) failures to explicitly specify important qualifications that researchers may take for granted in their own work due to overfamiliarity and (c) failures to fully appreciate, or at least make explicit, the indirect nature of their own enquiries into the phenomena of interest – that is, insufficient attention to the ontology of the phenomena they study. The aim in this book is not to diagnose which of these factors is likely to have contributed to insufficient clarity in particular research reports. Rather the purpose here is to clarify the nature of the research process in the field of research exploring student understanding, knowledge, thinking and learning so that readers of research reports can better 'read between the lines' – and to contribute to scholarship in the field, with the aspiration that authors, journal referees and editors might come to expect greater explicit clarity about the status of the entities referred to in research reports.

From my own reading of this literature, I have come to suspect that factor (c) may be quite significant in many cases – that is, many researchers are not sufficiently problematising the research process by being explicit about the assumptions underpinning their work. It will be suggested in the next part that a major factor is the way that research draws upon everyday 'lifeworld' terminology – in that there is a register of terms such as thinking, knowing, understanding and learning that are widely used in everyday discourse and readily understood at a non-technical level, but which lack operational definitions when adopted for research purposes.

For example, consider the following quotation from a research report published in the journal *Research in Science Education* in 1986:

> Various approaches have been used to identify students' understanding and misconceptions of science phenomena. Of these approaches, interview methodologies have acquired strong support as a viable approach… Although interviews with students have been successful in ascertaining students' understanding of science phenomena the interview methodology has possible limitations if it is to be used by classroom teachers. (Peterson, Treagust, & Garnett, 1986, p. 40)

The message here is clear. The extract suggests that interviewing is in principle a 'successful' approach to identify misconceptions and ascertain students' understanding in research – 'interviews with students have been successful in ascertaining students' understanding' – although the practicalities of classroom work make it problematic as an assessment tool for the teacher. I do not disagree with Peterson and colleagues: I consider that interviewing students is often the best technique to find out about their ideas and understanding of topics. However, there is a real issue here: How can we know if interviewing is 'successful in ascertaining students' understanding of science phenomena'? We could in principle know this if we already had independent access to students' understanding of science phenomena, when we could compare the outcomes of the analysis of research interviews with what we know about student understanding. If there was a good match, however defined and calculated, then we could be confident in the research technique. However, if we already had that knowledge, we would not need the research technique!

Shared Community Commitments

This is not a problem specific to science education of course but is a general issue in research. How does a scientist know that a particular technique can accurately date rocks, or find the energy of an x-ray emission, or identify a metabolic pathway? Ultimately all such techniques rely upon providing results that are consistent with a wide range of other measurements and evidence that we are reasonably confident in: usually in large part because they, in turn, are generally also consistent with what we feel is secure knowledge.

It is in this context that the ideas of Thomas Kuhn may be relevant. Although much of Kuhn's description of science and how it progresses has been criticised (Lakatos, 1970; Popper, 1970), his notion of scientists being inducted into a paradigm (T. S. Kuhn, 1970) or disciplinary matrix (T. S. Kuhn, 1974/1977) remains helpful. Part of Kuhn's thesis was that during what he termed 'normal science', the scientists working within a field hold a shared set of commitments (i.e. the disciplinary matrix). So in particular fields of scientific research, the existence and nature of electrons, the evolutionary relationship between particular groups of organisms, the mode of operation and interpretation of results from a mass spectrometer, the components of the human immune system, the means of denoting muons, the appropriate level of precision for citing the age of fossils, the appropriate way of interpreting temperature in terms of molecular motion, etc. come to be accepted by a research community and may be taken for granted.

In principle, at least, in science all such matters are provisional and open to revisiting in the face of new evidence – but for the purposes of normal scientific business, they can be considered as taken as given and *need not be argued from first principles in research reports*. In contrast, what cannot be assumed to be a shared commitment in the field needs to be justified in a research paper. So, for example, when ideas from one area of science are adopted in research within a different field, then journal editors and referees are likely to ask for justifications that would not be seen as needed in the host field.

One purpose of science education, especially at the highest (postgraduate) levels, is to train up new scientists, and this involves the induction of new researchers into the traditions and commitments that make up the norms and what is taken for granted in a particular scientific field:

> Kuhn's model of normal science education centres on the principle that the student is initiated into the dominant scientific paradigm of the day. A primary aim of science education, therefore, is to produce competent researchers, and research can only occur in line with the methods and concepts of the paradigm that define the puzzles being researched. (Bailey, 2006, p. 15)

Research in science education has sometimes been discussed in paradigmatic terms – for example, that constructivism forms the basis of the paradigm, 'as if a period of Kuhnian normal-science has descended upon the science and mathematics education communities' (Matthews, 1992) – but has never completely reflected Kuhn's ideas in terms of a set of shared community commitments at the ontological and epistemological levels. For example, Gilbert (1995, p. 181) noted that 'whilst the ethnographic/naturalistic research paradigm was developing, research within the older 'normative' tradition was continuing'.

Even though the premises of the constructivist programme as listed above (Taber, 2009b) would be shared by a good many researchers in the field (Sjøberg, 2010), there is no widespread agreement on how to operationalise the fundamental ideas underpinning these tenets in terms of the concepts most useful for carrying out and reporting research. To draw on analogies from the natural sciences, science education might be considered to be like the biological sciences after Darwin's ideas had been widely influential, but before anyone had a clear notion of where to look for the mechanism of genetic inheritance. Or, taking the physical sciences, we might compare the situation in science education to the state of affairs after Dalton had suggested the basis for modern atomic theory, but before there was agreement on the meaning of terms like atom and molecule, or anyone had clear notions of how such entities might be identified, or what kinds of interactions and structure they might have. Such 'ignorance' was still an advance, as the commitment to submicroscopic particles at least allowed the questions to be posed and so provided the impetus for research.

So in science education there was an 'explosion' of interest and activity in the field in the last quarter of the twentieth century that coincided with the development of widespread shared commitments to a constructivist notion of learning in science. However, that establishment of a central focus has not yet led to consensus models and constructs to describe, explain and explore the central concerns of the field encompassing student thinking, understanding and learning about science. In this sense, explorations of student thinking in science better reflect areas of enquiry such as personality or motivation in psychology (where there are widely discussed models and theories, and commonly used instruments, but no strong consensus), than many areas of the natural sciences where concepts are tightly described and standard instrumentation is well established. This is of course not a coincidence: the kinds of phenomena studied in the field discussed here (mental models, conceptions, understanding, etc.) are quite similar to many constructs studied in the behavioural sciences.

Being Explicit About the Frameworks Underpinning Educational Research

When new graduate researchers in education and other social sciences are taught to approach their research, they are commonly told that in setting out their work, they will need to present both a conceptual framework and a theoretical perspective for their study (Taber, In press). That is, they not only have to motivate their research questions by reviewing previous literature about what is already known, and where there may be 'gaps' in existing public knowledge, but they also have to justify how their research design will enable the production of knowledge of a suitable form to answer their research questions.

This is in effect *not* the methodology of a study in a specific sense (in terms of which research techniques are being used and how they fit into an overall design) but a step back to consider the paradigmatic grounds upon which a particular methodology (survey, experiment, grounded theory, case study, etc.) stands. There is a process whereby in approaching a study, the researcher is expected to move through at least three levels of thinking about what they are going to do: these may be considered (Taber, 2007, 2013a) the levels of philosophy (metaphorically, the executive level, setting out the paradigmatic vision), strategy (the managerial level of methodology) and tactics (the technical level of specific techniques).

Of course research journals cannot publish the level of detailed discussion of such matters expected in a graduate thesis. However, in many research papers published in science education, there is *little* explicit information for how a methodology was chosen in terms of the nature of the entities being studied and the nature of the kind of knowledge that the research might be able to produce. As well as limitations of journal space, this may often reflect the natural science background of many researchers in science education, where research training has traditionally been somewhat different to the social science model outlined above and where within an established paradigm the choice of methodology to approach a standard type of problem may often be seen as generally unproblematic (T. S. Kuhn, 1970). Perhaps it may not occur to some researchers that it is important to examine and present methodological justifications in these terms.

Whatever the reasons, many research reports on student understanding and learning in science education leave a great deal unstated about the fundamental nature of the entities they discuss and the status of the claims they make. (An example of the use of the term 'misconception' is discussed below.) For this reason this present chapter sets out an account of the overall process by which research in this field is carried out.

Claims About Technical and Common-Sense Notions

> We think we understand a word, such as 'cause', and as long as we keep going all is well. If we stop to analyse it, however, all is lost. In daily life, this odd phenomenon may not matter, but there are occasions in which it is important to know what we mean. (Johnson-Laird, 2003b, p. 41)

It seems that claims made in research reports can to a first approximation be considered to be of two kinds. Some reports make claims in technical language, for example, refer to such entities as 'alternative conceptions', 'p-prims', 'conceptual frameworks', 'mental models', …. By using such terminology the paper makes a claim that is explicit about at least some aspects of the way the researchers are thinking about learners' cognition or knowledge structures. Of course, there may still be issues about how such terms are defined, understood and used and the extent to which they are shared as useful constructs in the research community. There may also be issues of whether teachers can readily make sense of research reports using such technical terms. The latter point is important, for although most research reports are written primarily for the research community, most researchers in education are at least hopeful that their work can impact upon practice. There are good reasons to argue that research with direct classroom implications should be written up both for research journals and for practitioner journals, with appropriate conventions and writing styles according to the intended audiences (British Educational Research Association, 2000). So editors of research journals expect an account of methodology and appropriate referencing to the relevant literature that informed a study, where editors of practitioner journals often look for a focus on classroom relevance and application and often prefer a limited bibliography of useful further reading rather than a formal reference list. Often the different genres also involve distinct expectations about nomenclature – with technical vocabulary being more suitable for the research journal than the practitioner journal.

However, it is also clear from the examples presented above (see Table 1.1) that some research reports although published in the academic literature make claims using what seems everyday, non-technical language. These reports claim to tell us what learners (or teachers) 'think', 'understand' or 'believe'. Such writing certainly seems more reader-friendly: any reader of a journal with a good grasp of the English language will understand [sic] a statement such as 'students' *understanding improves* steadily as the course progresses' (Barker & Millar, 1999, p. 645), when not all will be familiar with specific technical constructs (e.g. such as p-prims or alternative conceptions; see Chap. 11) used in other reports.

Accounts that make claims in terms of learners' understanding or knowledge, or thinking, or beliefs may then be considered as more 'reader-friendly', in the sense of being more readily and widely appreciated, than those which describe findings in more specific technical terms. However, there is also an argument that such reports are open to more ready misinterpretation. If we all 'know' what is meant by a student understanding something, or knowing something, because in everyday life notions such terms as 'understand', 'know', 'believe' and 'think' are taken for granted, then claims phrased in these terms can also seem unproblematic. If we claim that a learner knew nuclei were positively charged or understood how acids reacted with carbonates, or believed that plants only respire during the hours of darkness, or thought that a continuous force was needed to maintain an object's motion, then we seem to be saying something very clear and definitive.

This would be fine if finding out what people know, understand, believe and think was straightforward (and if indeed knowing, understanding, thinking and believing were simple matters, open to pithy descriptions). Yet, taking an overview of the last few decades of research in science education, it is clear both that:

(a) These processes (knowing, understanding, thinking and believing) are often not simple matters than can be authentically described in simple statements.
(b) There are genuine methodological difficulties in finding out what someone thinks, believes, understands or knows in any definitive sense (as will be detailed later in the book).

The Value of Clarity in Language

This is not an argument for excluding everyday language from research reports. There is a strong case for 'headline' statements (e.g. in paper titles and abstracts) offering a very clear and straightforward statement of what a paper is about and what the researchers think they have found. Indeed given the lack of consensus on the technical terms used in this field (conceptions, frameworks, etc.), there is a strong argument for ensuring that all researchers can quickly identify papers likely to be relevant to their research regardless of the specific conceptualisations and approaches adopted in different studies. Pithy statements referring to such everyday notions as students' knowledge and understanding can be very valuable in this regard.

However, it is argued here that the same clarity that can offer a quick impression of what a paper is about can also lead to researchers with different understandings and assumptions about what is involved in understanding or knowing, for example, misinterpreting what a study actually offers in terms of new knowledge. However, this should not happen if the 'headline' claims are underpinned by more technical explanations of the research. Research papers should of course make it clear just what is being claimed and how the research undertaken supports those claims. However, it is suggested here that research in science education often falls somewhat short of being fully explicit about such matters. This may be because researchers sometimes assume others working in the field will share what they see as obvious assumptions and commitments, or it may sometimes be because the researchers are working with a good deal of tacit knowledge (Polanyi, 1962) – that is, drawing upon assumptions which are so well established in their thinking, they are implicit in the researcher's work and are not 'brought to mind' when writing reports.

Making the Research Process Explicit

Inevitably we all operate with a great deal of tacit knowledge, and indeed we could not function in any sphere of life if we had to stop and analyse everything we do (every keystroke I am making now – what am I doing, and what do I expect the outcome to be?) Humans only operate at the higher levels of cognitive function because our cognitive apparatus allows us to automate so much (see Chap. 7).

However, when it comes to research, there are some things that need to be made explicit for a research report to provide a sufficiently detailed and clear account of our work. Unsurprisingly, these relate to ontology and epistemology. If we wish to investigate, for example, student understanding, then we need a clear idea of what kind of thing 'understanding' is, that is, we need to operationalise it as part of our 'conceptual framework' setting out the background to the study – what existing research already suggests. We also need a good idea of the kind of knowledge it might be possible to develop about another person's 'understanding', informed by the 'theoretical perspective' that with the conceptual framework justifies the methodological choices made during the research (Taber, In press). What is being argued here then is that in our field of research, these aspects of the research report are often limited and inadequate.

An Example of a Study Reporting Student Misconceptions

To illustrate the nature of my general argument here, I wish to briefly consider a paper from an international research journal in the field, which discussed an aspect of learners' 'misconceptions' in a science topic (Banerjee, 1991). I have not identified this paper as being especially problematic, and indeed I feel it makes a useful contribution to the field. Rather, I suggest that it is somewhat typical of many papers published in the research literature about aspects of students' ideas in science. Additionally, it usefully – for present purposes – uses the key term (here, misconception) throughout the text and is consistent in using *that* term (rather than preconceptions, alternative conceptions, alternative frameworks or other related alternative terms). This allows the preparation of a useful concordance of each time the term is used in the paper (excluding the reference list), which is presented in Table 1.2:

Reading of Table 1.2 obviously only gives a flavour of the full paper, but it demonstrates that the notion of a misconception is not explained in any detail: there is not a part where the author feels the need to explain to the reader what is meant by the term 'misconception' in the context of this paper. By the time of this study, the term misconception was in widespread use in science education, and the author presumably felt that it was well enough established that the readership of research journals in the field would know what was meant. The Banerjee paper is some years old now, but at the time of writing, papers in top journals continue to use terms such as misconception in a taken-for-granted way (Bivall, Ainsworth, & Tibell, 2011; Jaakkola, Nurmi, & Veermans, 2011; Ratinen, 2011).

We might expect to see a similar approach in mature scientific fields: for example, papers in chemistry research journals that refer to something being a 'compound' do not usually explain what is meant by the term. It can be taken for granted that the readership of research literature will share a common understanding of the term: something that would not have been the case when the term 'compound' was first being mooted and had not been widely accepted in the discipline. For compound, we can substitute any number of now accepted terms: gene, energy, neutrino, tectonic plate, brown dwarf, etc.

My argument here is that where within the natural sciences, there are mature fields where it is reasonable to assume other workers share a fairly close understanding of what is denoted by common terms, but science education does not yet have this level of maturity (Fensham, 2004), and many terms are used in looser ways. As well as science education being less 'mature' than fields in the natural sciences, it also deals with subject matter of an inherently different nature, due to the complexity of the phenomena studied in behavioural and social sciences (Taber, In press).

Table 1.2 Concordance for the term 'misconception' found in Banerjee (1991)

Paper part	Occurrence of term 'misconception'
Title	'Misconceptions of students and teachers in chemical equilibrium'
Abstract	'A written test was developed and administered to diagnose misconceptions in different areas of chemical equilibrium…'
	'Analysis of the responses reveals widespread misconceptions among both students and teachers…'
Introduction	'There is a large body of research on the misconceptions of students in a variety of science subjects…'
	'The usual method for obtaining information about students' misconceptions has been through individual student interviews'
	'… used interview techniques to study misconceptions of students in stoichiometry and … in chemical equilibrium'
	'Another line of research on misconceptions uses multiple-choice tests'
	'… and … developed and used tests to identify misconceptions of year 11 and year 12 students about covalent bonding and chemical structure'
	'The present study covers broad aspects of chemical equilibrium including gaseous, ionic, solubility and acid-base equilibria, and diagnoses misconceptions among 162 undergraduate chemistry students'
	'To obtain information on the question of whether misconceptions are removed with increased content knowledge and experience, the diagnostic test was also given to 69 secondary and senior secondary school chemistry teachers. Apart from knowing whether teachers also have misconceptions in the areas of equilibrium, the study would indicate whether misconceptions among students may have originated from the misconceptions of the teachers'
Development of the test	'An analysis of the responses indicated widespread misconceptions'
Administration of the test	'However, conceptual difficulties and misconceptions in the different areas of equilibrium were not specifically covered in these lectures'
	'In this paper, the discussion is concentrated on 12 test items (listed in the appendix) which were used to diagnose conceptual difficulties and misconceptions…'
Analysis and discussion	'Misconceptions were mostly identified from the explanation given in support of the answer by the student and teacher'
	'These responses, in general, indicate widespread misconceptions among both teachers and students in topics relating to…'
	'A sizeable percentage of teachers and students have the misconception that…'
	'Similar student misconceptions were reported by…'
	'There are widespread misconceptions in the areas relating rate with equilibrium'
	'They have the misconception that a large value of equilibrium constant implies a very fast reaction'
	'Similar misconceptions have been reported by…'
	'However, the present study clearly indicates that the rate approach should be used with caution and should not be overemphasized, in order to avoid the possible development of misconceptions'
	'Students and teachers show a high rate of misconceptions in acid-base and ionic equilibria'

(continued)

Table 1.2 (continued)

Paper part	Occurrence of term 'misconception'
	'A comparative study of the responses given by students and teachers reveals that the extent of misconceptions is equally high among both groups. One possibility is that teachers might have developed these misconceptions during their student days. The misconceptions are retained, despite professional experience over the years'
	'According to the general constructivism theory of knowledge … it is very difficult to remove misconceptions from the minds of learners. The findings of this study on misconceptions among students and teachers should not be treated as specific to this sample. Many misconceptions of a similar nature about chemical equilibrium have been reported with students from Australia and the United Kingdom'

A hypothetical scholar from a distant time or place who did not know what a twentieth century science educator might mean by 'misconception', and finding that Banerjee did not define this term, could look for clues in the text and attempt some kind of hermeneutic exercise to tease out what a misconception might be. We can find in Banerjee's paper a number of knowledge claims about the nature of misconception deriving from the study:

- Some misconceptions are widespread among students and teachers.
- Some misconceptions occur at an equally high rate among students and teachers.
- Particular misconceptions may be had [held] by substantial proportions of the sample.
- There can be degrees of similarity between different reported misconceptions.
- The development of misconceptions may be facilitated by teaching approaches.
- Misconceptions can be retained for extended periods.
- Misconceptions can be very difficult to remove from minds.

These claims derive from a study that is set up in a particular way because of the researcher's assumptions about the nature of misconceptions (i.e. ontology) and how one could investigate them (i.e. epistemology). Epistemological assumptions informing the research would seem to be that:

- Misconceptions may be diagnosed/identified by written tests – for example, from justifications of respondent answers.
- Misconceptions may be explored through student interviews.
- Misconceptions may be diagnosed with multiple-choice tests.

Ontological assumptions (the researcher's assumptions about the type of entity misconceptions are, i.e. their nature), which support these epistemological assumptions, would seem to be:

- Misconceptions can be widespread.
- Misconceptions can occur among students and teachers.
- (And more particularly) misconceptions are found among undergraduate students.
- Misconceptions can relate to a variety of science subjects.

- Misconceptions occur in the minds of learners.
- Misconceptions are the kind of things that in principle could be removed.
- Misconceptions may be passed from individual to individual.
- Misconceptions could potentially be ‘covered’ in lectures.

These qualities of misconceptions are largely assumed by the author and are implicit in what is written, and, I would suggest, only one of the points here (namely, misconceptions occur in the minds of learners) reflects the essential quality of misconceptions that is the central focus of the paper. It could be argued that research reports of this type suggest the reported studies may themselves be under-theorised, as rather well-defined technical procedures are used to investigate foci that are themselves only vaguely characterised, and so the technical procedures are themselves largely operationalised without explicit rationale. Whilst I have examined one study in some detail here, similar analyses could be obtained for many of the papers reporting empirical results in this field.

Knowledge Claims Need to Be Understood as Being About Models

So a central argument of this book is that research reports need to be more explicit about the processes by which we feel we can make claims about aspects of a person’s knowledge and understanding in science. In particular, I will argue that such research involves a series of modelling stages. Consider, for example, the question what do 15-year-old students (in some educational context) know about photosynthesis (or atomic structure, or the electromagnetic spectrum, or plate tectonics, etc). If our focal topic were part of the school curriculum, we might expect that a key source of any knowledge they may have would be expected to derive from teaching. Figure 1.3 sets out in schematic form the key modelling steps both in the teaching process and in the research process.

The left-hand side of the figure illustrates something of the processes by which scientific knowledge is transformed in the curriculum and classroom and then interpreted by the individual learner in forming and developing their own mental models of scientific concepts (Gilbert, Osborne, & Fensham, 1982). A key point here is that the ‘standard’ by which student knowledge and understanding is usually judged in educational contexts is not scientific knowledge itself, but a specified target knowledge in terms of a prescribed curriculum. That curriculum will include models of the scientific knowledge (Taber, 2008b). In part, this will be a deliberate modelling process, designing appropriate simplifications for learners of a certain age and expected background knowledge; in part, it will be the inevitable limitations of curriculum developers themselves in knowing and understanding the latest scientific knowledge.

Moreover, the curriculum models are generally moderated by the presentation in class and in textbooks (Chevallard, 2007). The teaching models presented in class will be based upon the curriculum models as understood by the teacher but may

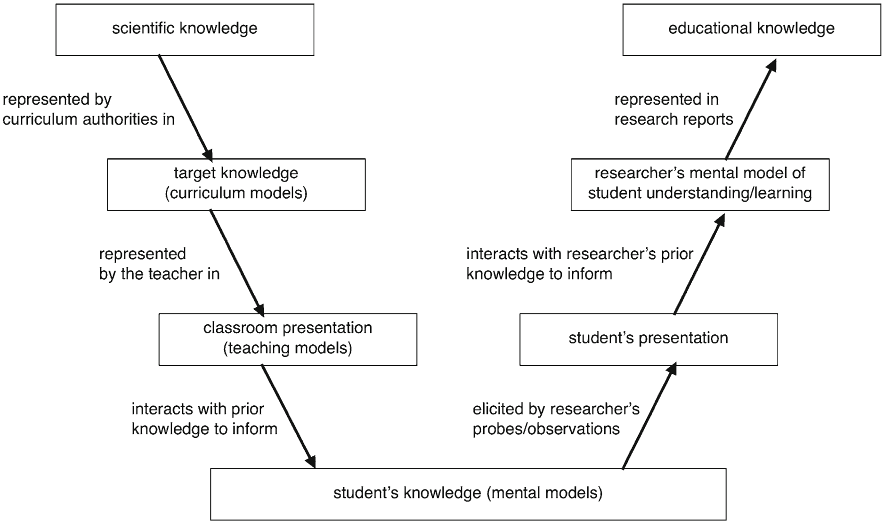

Fig. 1.3 Overview of the process of producing educational models of student understanding of scientific knowledge

include further simplifications, taking into account the specific class of students, or distortions (if the teacher does not fully understand the target knowledge). Even if there is limited deliberate modification of target knowledge, there will always be potential for distortion of curriculum models as the process of teaching inevitably involves processes of re-representation (Taber, 2009b, p. 46, fig. 4.1): the curriculum documents are read by the teacher who forms some kind of mental representations of them so the knowledge represented in the curriculum documents is re-represented in a different form (this is discussed in Chap. 4) and then presents an account of his or her understanding in talk, gesture, written inscriptions, etc. in the classroom, so re-representing the mental representation in public communication.

This set of processes is well described in literature (Gilbert et al., 1982), and Fig. 1.3 shows how a similar set of processes are usually involved in research exploring aspects of student knowledge and understanding. The right-hand side (rhs) of the figure offers an overview of the processes by which researchers develop representations of student knowledge to report in the literature. The result of this process is formal public knowledge (a notion explored in Chap. 10).

Knowledge claims made in literature rely upon the cases – argument chains, supported by warrants (Toulmin, 1972) – made by the authors for the interpretation of evidence collected in research, informed by the researchers' own conceptual and theoretical frameworks. In the case of scientific knowledge, the conceptual frameworks will normally be based upon widely accepted principles (e.g. natural selection; molecular orbital theory, etc.), and the theoretical principles underpinning data collection and analysis (e.g. C-14 dating; PCR analysis of genetic material, etc) will also be widely accepted (T. S. Kuhn, 1996). Whilst the production of educational knowledge (i.e. the rhs of Fig. 1.3) parallels that in the natural sciences, the assumptions made by researchers are less likely to be so widely agreed within the research community (Black & Lucas, 1993b). Therefore, it is important that researchers' accounts are explicit about the assumptions underpinning their work to allow others to make considered judgements about their claims (Taber, 2007).

This volume then explores the processes by which knowledge claims about students' knowledge and developing understanding are produced: processes that at their core involve researchers collecting and analysing evidence *to build models* (1) of learners' knowledge and thinking and (2) of the shifts in that knowledge associated with learning and conceptual development.