Chapter 5
Illuminating Scientists' Modeling Competence

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5.1 Introduction

There is the assumption that models and modeling are central to a scientist's work. In an attempt to find out how scientific knowledge is generated there have been efforts to monitor how they develop knowledge – for example with Latour and Woolgar's (1986) seminal work *Laboratory Life*. This ground-breaking research enabled non-scientists to glimpse into the organised chaos of the laboratory. Since then research on how science knowledge is developed has become central to science education at all levels.

Furthermore, this educational focus on understanding the epistemic role of models is justified when Gilbert, Boulter and Elmer (2000) wrote and edited the seminal book that argued for the central role of modeling in education about science. Their justification was based on the premise that models were one of the main products of science (Rosenblueth & Weiner, 1945). Consequently, this chapter's focus on describing and analyzing how scientists perceive the nature of models that they construct, test and adapt has the potential to frame some indication of competence.

5.2 Justification for Interpretation Rather Than Assessment

Adding to the complexity of analyzing scientist's use of models is that they employ diverse research approaches. Schwartz and Lederman (2008) identify four research approaches used by scientists – that is experimental, descriptive, experimental/descriptive and theoretical. Then there are the six styles of scientific reasoning

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proposed by Kind and Osborne (2017) underpinned by three forms of knowledge – i.e. ontic, procedural and epistemic constructs that scientists weave together as they pursue better explanations of phenomena. Coupled with the diversity of contexts that can affect the research focus within a domain, there are instances of applied research where the wider perspective encompasses practical usefulness as well as the epistemological scientific goal of truth (Olsson, 2015). Furthermore there is diversity in how the model is used. For example a model can provide a theoretical expression of a paradigm through which data is interpreted. Another more practical view is when a scientific model is thought of as a 'surrogate' – that is a technical version of the substitute (Adúriz-Bravo, 2013). To add to the complexity of the use of models in experimental design is that when scientists are thinking about how to best represent the target, they can select aspects of this target when deciding the focus of their research. Consequently their selection and adaptation of a model is particularized for each research situation for one that best provides a bridge between theory and phenomena (Oh & Oh, 2011).

With all of these variations in model use and purpose it could be pertinent to explore the possibility of assessing scientists' models and modeling competence (MC) alongside the comprehensive description of model use by scientists (Van der Valk, Van Driel, & De Vos, 2007). Although these researchers do provide a descriptive framework, their description does not allow space for an analysis of scientists' MC. Closer to this focus on competence is an identification of students' understanding of models and modeling by Upmeier zu Belzen and Krüger (2010) where they present a matrix that identifies not only five aspects of models but propose three levels of student understanding.

Nevertheless, it would be impertinent and unproductive to equate even these high levels of student understanding with an assessment of scientists' MC. Because scientists are immersed in model development and use within their research, and not as onlookers as students are, attempting to assess scientists' MC would be equivalent to assessing their 'knowledge about science' that is the Nature of Science rather than assessing how they have created 'scientific knowledge'. Furthermore it could be asserted that the complexity of model use by scientists would be difficult to unravel, let alone assess. Rather than focusing on assessment it could be instructive to explore the way in which scientists talk about models and their purpose as a way of interpreting their competence. Consequently the focus of this chapter is to recount with some comment scientists' stories of how they use models in their research because this approach was considered to be more enlightening for the reader than a direct assessment of competence. It is proposed that such an account would illuminate how a scientist viewed the nature of models, their purpose, and how they tested and evaluated the models they used in their scientific practice. Furthermore when appropriate an interpretation of an example of these scientist's modeling competence will be explained with reference to the framework for modeling competence (FMC; Chap. 1) and modeling-based Learning Framework (MLF; Chap. 3) that could be given some attention.

It is proposed that following indicative questions about the character and use of models could provide access to scientists' thinking and provide a framework for this analysis. These indicative questions are derived from the author's interpretation of Van der Valk et al.'s (2007) description of the nature and functions of models (pp. 471–472).

It could be presumed that scientists' awareness of the potential and limitation of models in their quest to discover answers to 'why' and 'how' questions about phenomena would provide some enlightenment about the complexity of the scientific process. In the following account these areas will be related to the story of how each scientist uses models in their research and, (rather than assessment), illustrative examples of their competence will be provided. The following questions will provide a framework for these scientists' accounts and provide illustrative examples of the theoretical FMC as discussed in Chap. 1 and how an understanding of the Nature of Science can deepen this analysis (Chap. 4).

- How do scientists perceive models? What are their understandings of the nature and function of models in research?
- What are their understandings of the relationship between model use and knowledge development? How are these epistemological relationships expressed by scientists?
- How do scientists develop models? What is their awareness between the relationship between questions asked and data generated?
- What do scientists say about the limitations of models? How are their epistemological understandings expressed?

5.3 Using Models in Research Science: Scientists' Stories

In order to describe and analyse how scientists viewed and used models, two scientists were identified via a snowball sample – that is a non-probablility sample in which the researcher makes initial contact with a group of people (practising scientists) who establish contact with others who can respond to the researcher's request (Bryman, 2004, p. 544). These scientists were interviewed to find out how they used models in the process of knowledge development. The following questions guided the direction of these conversations:

- Tell me about a research that you have been engaged in that uses models?
- What models do you use in your research?
- How do you use models in your research?
- Do you use more than one model in your research to represent the same explanation/data/prediction?

As part of the ethics process the chapter was returned to each scientist in order for them to check their contributions so that their quotations provided an accurate scientific account of their research. Because it is not possible to provide anonymity for these two scientists as they and their research are well known in New Zealand and at Auckland University, it was mutually decided by participants (scientists) and the researcher that both scientists would be identified, and an article that best represented this aspect of their research would be included in the literature review. Siouxsie a microbiologist investigating the evolution and transmission of as well as drug testing on pathogenic bacteria and Laura a perinatal systems physiologist who uses sheep models to provide clinical data – have agreed to allow their quotes to be acknowledged by name. They have provided papers that give more detail and context to the research they are discussing (Dalton et al., 2017; Bennet, 2017).

As this research is conducted within an interpretativist research paradigm a narrative was constructed from the scientists' quotes that best answered the questions posed (France, 2010). Because the focus of narrative enquiry is to provide an opportunity to create further meaning for the reader (Connelly & Clandinin, 1990) the narrative was constructed under the headings that provided links to these scientists ontological view of models, their epistemological beliefs, the procedural knowledge that underpinned the way they used models in their research design – that is their generative data capacity; as well showing that these scientists have a keen understanding of the limitations of models when interpreting data.

During the process of constructing the quotes that provided illustrative data about these scientists' perception and use of models the following components were paid attention. These were:

- The establishment of a collaborative relationship between the researcher and scientist that enabled the construction of these illustrative excerpts. For example the invitation was accompanied with an explanation of the expected outcome – i.e. the book proposal
- Using a process that enabled participants and scientists to make sense of the data and developing story (Bryman, 2004). For example the chapter was returned to the scientist to ensure the excerpts best reflected the explanation and interpretation of how they used their models.
- Establishing that the completed narrative reflected the complexity of the underpinning material that demonstrated the apparency and verisimilitude of the outcome (Connelly & Clandinin, 1990; Clandinin & Connelly, 2000). For example scientists were asked to provide a published research paper which exemplified how they used models in their research. These papers were included in the reference list.

In summary the illustrative narrative excerpts were constructed so that the reader could become independently aware of these scientists' theoretical perspectives of model use and limitations as well as the constructs that underpinned their procedural and epistemic knowledge. It was expected that these illustrative narratives would ensure that the scientist's competence when using models in their science practice would be illustrated (France, 2010).

5.4 Results

5.4.1 Siouxsie: A Microbiologist

Siouxise is a microbiologist who combines her passion for exploring the phenomenon of bioluminescence with her research on infectious diseases in order to understand not only how pathogenic bacteria adapt and evolve, but also to develop new antibiotics to kill them. She summarises this research focus by saying that she and her team make nasty bacteria glow in the dark in order to find new medicines.

Because one of the bacteria under research is *Mycobacterium tuberculosis*, which is very difficult to kill, spreads through the air and deadly (it is the cause of tuberculosis) – Siouxsie requires highly specialist containment laboratories in which to carry out her research. This bacterium, as well as being restricted to laboratories with specialist people who can work with the bacterium, there are limited surrogate hosts that provide source data for scientists when studying this disease and its control.

Consequently, models are central to this research group's experimental research. The substitution of models takes into account the danger and cost of working with the tuberculosis bacterium as well as needing to use a surrogate host instead of humans. This research team works with *M. tuberculosis* and a variety of closely related bacteria to replicate its growth in vitro as well as in vivo in model animal hosts such as mice. They often choose alternative microbes from the same family as *M. tuberculosis* that are less dangerous but provide important source information about its physiology and infection patterns. Furthermore, the substitutions of host and micro-organism can be studied as a model system where the surrogate microbe and surrogate host can also provide source knowledge about the target.

Siouxsie's comments about the range of models used by her team demonstrate that she has a high level of MC in that the model and model system she selects depends on the nature of the question she is investigating.

> My research uses lots of different models... and model systems. We have model hosts for the different infectious diseases. We would use different model systems depending on the organism we are asking questions about and the type of question we are asking. For example, we use different models to simulate the way the bacteria might be behaving in the human body.

Her understanding of the nature and role of the models used in her research is apparent in the following comments. Siouxsie's view is that a model is a research tool that is used to obtain information about the target which itself cannot be easily observed or measured directly. Consequently she needs to model these microbes' growth in the human or animal host – hence creating an environment to best replicate the human or animal host.

> Our model is a thing. Our models are the bugs we grow in a particular way to model what is happening in the human or animal host.

She comments that the purpose of this model is to:

> Try and replicate in the best possible way … with all the limitations we have (ethical constraints, financial constraints) … what might be happening in reality. It is a living model and more complex.

However this replication was more complex than attempting to recreate an idealized representation of the original because she and her team needed to take into consideration other issues than just the replication of growing conditions. Consequently the factors that influenced the development of this model involved deciding if the use of an infectious dangerous microbe was ethical and worth the expense of using specialized expensive staff in a specialized containment laboratory. During this stage of the researchers were investigating 'how can this microbe be grown that best replicates the host organism environment within the limitations of this research design?' New knowledge was being developed about the best growing conditions rather than scientists making an adjustment to the environmental conditions.

But her view of a model is more even complex as she notes that the substitute organisms and host systems are various. For example:

> We have the tuberculosis bug that we can use on its own and we can infect mice. And then we have several relatives of tuberculosis – the main one that we use is *Mycobacterium marinum.* We use it alone and we use it [to infect] zebra fish embryos and now we have put it into caterpillars.

It is significant that the use of model systems is a focus for Siouxsie's team. In order to replicate the way this bacterium grows in the host, decisions need to be made not only on the choice of bacteria but about how the organism will be grown – that is in vitro or in a surrogate host which could be a zebra fish embryo or a mouse. All of these decisions are focused on providing source data material that can supply pertinent information to predict how bacteria might behave in the target (human body). She states:

> We have model systems that are about the way you grow the bacteria. For example, bacteria can form communities and grow biofilms.

Making choices about how to model the micro-organism's physiology, method of infection, and ultimately its evolution into different pathogenic strains is central to these scientists' thinking. It is apparent that they are equating within their experimental design the analogous relationship between source and target all the while using this situation to predict what could happen in the human host – this is an example of sophisticated thinking about how to test the original hypothesis.

The following account of how Siouxsie's team developed the zebra fish embryo model for drug testing demonstrates that a model will always be the result of the compromise between the demand to best represent the target and a simpler model that can be managed in the laboratory. These developmental decisions reflect the nature of the research problem, the facilities available to more experienced members of the research team as well as providing an opportunity for researchers who are not qualified to work with such dangerous organisms. Consequently time, money and expertise issues as well as the personal preference of the researcher will influence what models and model systems are developed.

Siouxsie's account of how her team developed the zebra fish embryo model for drug testing also demonstrates how collaboration and dialogue between different research teams with different research agendas can influence the way in which models can develop.

The overall focus of Siouxsie's team was to find out how to "speed up drug discovery for tuberculosis by letting it be applied in wider labs in an easier way". The group were seeking the development of a consensus model that was not only quicker and involved more humane methods but enabled access to laboratories who might not have the facilities for drug testing on infectious human diseases.

> Doing this drug testing in a more humane way that would be quicker and could also be used by other labs - maybe labs that don't do any animal work or don't do any mammal work. So maybe they have a zebra fish facility and if they could do some of this drug testing in their labs.

Her group were aware that zebra fish embryos are a widely used model for research – for example on the immune system. These embryos are used at about 3 days after fertilization, that is before they have developed systems for sensing pain. Their bodies are transparent so it is possible to observe them under the microscope and the location of invading bacteria. She observes that what makes these embryo hosts so valuable is that they are "easy to genetically modify and there are versions of these zebra fish that have different types of cells that are labelled in different colours".

At this stage of planning for this model development Siouxsie's team had genetically engineered, for another research group, a relative of the tuberculosis bacterium that glowed in the dark when alive.

Siouxsie's group realised that this bacterium could provide a model for their own research. But the problem for Siouxsie's research team was to find a way to infect the embryo that did not involve yet another high level of expertise and equipment in addition to that occurring in their microbial research. Normally zebra fish embryos are immobilised and then bacteria are injected directly into different parts of the body which involves a complicated technique and requires a high level of skill. Siouxsie wanted to develop a model system of infection that didn't require such a level of skill from laboratory personnel. She used bacteria that were similar to tuberculosis bacteria but not dangerous but the problem was to find a method of infecting zebra fish embryos that was less expensive and did not require a highly skilled level of personnel to infect the embryos. "Something that could maybe be applied more widely and didn't require such skill and could maybe be automated."

Siouxsie was able to draw on her post-doctoral experience where she worked on a model system that compared the infecting of organisms using gastric gavage (where the dose of bacteria is introduced into the animal's stomach with a blunt needle) with a method of infection that more closely mimicked normal conditions. She drew on her past experience and knowledge to reflect that these embryos would be naturally infected by substances in water and developed a system to infect them naturally by adding the bacteria to the water in which these embryos were swimming.

Consequently, Siouxsie's team were able to adapt this model system so that less dangerous bacteria could be used to infect zebra fish embryos that were more accessible to other research teams testing drugs.

This alternative method of infection added to the range of the potential model systems available to Siouxsie's research team. As well as testing different drugs on the tuberculosis bacterium growing in the flask in vitro, her team have developed model systems that provide different infection routes, that use identified relatives of the tuberculosis as well as alternative surrogate hosts such as mice and zebra fish embryos. This variety of bacteria, surrogate hosts and transmission systems increased the potential for providing model systems for drug testing. Her comments indicate that she has not only provided multiple models but also new pathways for future research:

> More people can use this model system to progress the research further to get more people involved who can then say right we have now developed all these drugs can some now try them against the tuberculosis bacterium. Now we have more confidence that they will work.

However, Siouxsie is pragmatic, realising that not all models provide the source information that is expected. She described an evolution experiment that she planned which would use versions of bacteria that were coloured green and red. She had anticipated showing by colour which population of bacteria became more dominant in a culture or an infected host. However, the research team were unsuccessful in developing these differently coloured bacteria for these experimental conditions so they reverted to a previous developed method of using different varieties of bacteria that glow or not. As Siouxsie comments.

> We tried to adapt this model so we can do our really cool experiments in a really cool way. With the colour difference we could look at how they changed. For example, in an animal you could see that one is better than the other because the infection would become predominantly green or predominantly red. It didn't work so we are doing to these experiments anyway. Instead we competed the bacteria with a [with]one that glowed in the dark. We infected mice and then asked the question – do they end up with a tummy full of glowing bugs or a tummy of non-glowing bugs*?*

Siouxsie's description of the changes of direction that this research took illustrates that she is aware that living models do not always provide data that is expected and her expertise is demonstrated in that she was able to make the most of this failure of research design and revert to an earlier technique that provided data that could test the hypothesis. Such adaptability of the researcher as part of the aspect changing model in the FMC could be considered in future iterations of the FMC more explicitly.

5.5 Summary

Siouxsie's description of model use in her experimental research shows her level of expertise and that modeling took centre stage. For example in order to carry out this research there was a need to develop surrogate model systems that provided information about the source organisms that could enable drugs to be tested. This source data was used to identify potential drugs that have potential to kill the target bacteria – that is *Mycobacterium tuberculosis*. Because of Siouxsie's knowledge of source microbes and hosts and her awareness of the limitations of developing drug testing on human hosts, she designed this research using a variety of model systems. The implementation of these model systems shows a deep understanding of the potential and limitations of what source information can be produced that can support a theoretical prediction about the phenomenon in question. For example not only did she use microbial models to test drugs, but also she employed a variety of host organisms in which the microbes were grown – that is mice, zebra fish and caterpillars. Furthermore Siouxsie extended the capacity of the model system to enable other researchers with less expertise and without high performance laboratory facilities to take part in this adapted experimental design.

Such a capacity to produce this variability of research design demonstrates a deep and sophisticated level of understanding of the role of models and model systems in her experimental research.

5.5.1 Laura: The Perinatal Systems Integrated Physiologist

Laura leads a team researching perinatal physiology within the Faculty of Medical and Health Sciences. She describes herself as a perinatal systems integrated physiologist.

> [My research is] in fetuses and newborns, so, babies and I'm particularly interested in babies before they're born, particularly pre-term babies and how they grow and develop. How they cope with adverse events in their environment, what causes injury and what we can do to: (a) detect it; and (b) to try and ameliorate that kind of injury or prevent it. We are in the business of understanding basic physiology with a clinical translation or medical component in it. We [research] about what we can do to help these babies and newborn.

Laura reflects that collecting data from the fetus is problematic but crucial in order to establish developmental patterns from detailed physiology information on blood pressure, blood flow into organs, heart rate and brain activity. More importantly, because fetal injuries evolve over a long period of time, this physiological information needs to be recorded throughout the pregnancy in order to provide long-term information. She observes that once these developmental patterns of data are established, there is the capacity to identify environmental challenges to the fetus such as inflammation and hypoxia (oxygen deprivation). Because it is impossible to carry out such an interrogation of a human fetus, a chronically instrumented fetal sheep has been developed for an animal model. The sheep model has been selected by this research team because there are similar parameters to a human fetus in that it is a similar size, and at certain periods of its development it equates to the physiology of the human. These animal models are prepared by inserting recording devices into the fetus during an anesthetized caesarean section. After the fetus has been replaced and the host animal has recovered, data are collected while the mother sheep is exhibiting her normal behavior.

Laura comments on this model which she describes as "a paddock to bedside to cot model".

> This is a very powerful systems physiology model – that is we are looking at various systems together. We are looking at the physiology of the fetus itself. We can look at its blood pressure and its brain activity and its body movements that make the physiology of the animal and mediate injury. There are bi-markers that we can take to clinic to say – if you see this pattern of activity of body movements or heart rate then we know the baby is in a state and is doing this. And once you are understanding the physiology of what is going on you can begin to layer in potential treatments.

The focus of this model was to provide information about how to treat newborn injury that can result from a difficult birth – for example brain tissue inflammation and oxygen deprivation. It has been found that cooling the fetal brain can improve outcomes and the data from the fetal sheep model has provided information for this procedure – for example when to start, for how long, when it is too late, its effectiveness, timing and dose. This information provided data for international clinical trials of the cooling-cap treatment which nowadays is a standard of care that when there is a clinical diagnosis of damage to the newborn.

Laura's view of models and modeling shows a sophisticated view of its capacity to represent the target under research. Her level of sophistication is apparent in the way in which she reflects on the role of models in scientific research where she uses models as a tool for collecting data.

> It all comes down to the question that you are asking. Models are a tool and not the solution … because you can do a technique – that is not science. The science is the question. The question is 'what do I want to know?' and then 'how do I then get the data that is going to support the question that I am asking or the hypothesis I'm generating?'

As well as demonstrating her epistemological awareness of the role of models and their function she expresses the thinking that must occur when designing a model that can provide a valid representation of the phenomena under examination. Furthermore, she observes that the researcher needs to be very aware of the differences between the source (animal model) and the target.

> So constantly you are asking yourself - what is the clinical scenario? What is it that I'm physiologically monitoring? It's always about the question. And therefore, you adapt it to the scenario that relates to the question. And you layer it [the model] up depending on what information you need to show … either physiological changes or molecular changes or chemical changes … whatever you need to do to add to your recipe for that experiment.

> So the hypothesis is the key scientific element of an experiment. Then you have to look at how you will address that in terms of the model you might use. We need to be very careful

> about any animal model ... for example in terms of equating it to certain comparisons to a human because sheep stand up when they are born, and feed and run around. Humans don't, so we have to be careful that we have got the right timing.

It is very apparent that Laura and her research team not only have searched for a close analogy that provides data for the target but they are constantly critiquing the model to provide the best clinical data that can be used for treatment.

Because there is a clinical focus for this experimentally obtained source data, a lot of time is spent developing the model. As Laura comments.

> It is not something you can pluck off a shelf and say 'ok I am going to do this model today'. You actually have to set in and experiment around the parameters of what timings you are using, what ages you are using, what might cause inflammation. There is a lot of experimentation around just establishing a model let alone using it.

This aspect of MC is not able to be assessed using the model proposed in Chap. 1 as there is no space given to an analysis of how the thinking underpinning how models are developed. It appears that the testing of a model's category does not seem to encompass the deeper level of analysis that is required when the model parameters are identified that can affect the research design.

It is apparent that Laura has a deep understanding of the nature of models and that more than one model may be required to provide different data sources. Laura notes that one model isn't necessarily a fit for all purposes. She makes the observation that a model may be developed to provide specific source information and comments that often questions needing experimental data to answer them are set in the model, for example when a model is designed to provide source information about what is happening in the fetal brain during labour. She comments.

> For example, I am using a model where I might just give a single squeeze of the umbilical cord to [provide] a period of time of low oxygen to the fetus – which often happens at birth. But actually in labour you have repeated squeezes because that is what contractions are about. That is a different model and you have to develop that as a separate model. So the questions are set in your model.

An awareness of the epistemic demands of this source data means that the experimental design must reflect this model's capacity to provide pertinent data. Consequently, Laura and her team pay attention to the statistical representation of the data.

> You need to apply your statistics before you even start your experiment. That is - the right group-size number, group-size setting well before you start your experiment so you've got power over the statistics.

Laura states that the function of her models are the testing and revision of scientific theories. She notes that "a good model should be robust". She reflects that her model provides predictable data when trauma is applied to the sheep fetus. It is significant to acknowledge that her claims for robustness are set strongly within the framework of the experimental design and indicates her awareness of the nature and function of this model that will provide data from which scientific theories about cause and recovery theory in the human fetus and pre-terms can be developed.

> My model for pre-terms is now around the world because I tested it robustly and it took a long time to get 'yes' under these situations. I'm not claiming it to be anything else but this condition under this situation – this is what this model is producing and if you do it this way it will produce this pattern of brain injury.

Because she is acutely aware that the fundamental principle of science is not to be biased towards one's original hypothesis, her commentary also acknowledges the limitations and caveats of the model:

> We are using sheep. We don't know necessarily about the sheep differences. By definition it is no longer a normal in utero environment because you stuck a lot of tubes and things in it.

But Laura and her research team are not just restricted to experimental modeling – that is using a model as a surrogate research animal. She is also developing theoretical models when dealing with the data that can inform further model development within an experiment.

> A theoretical model can use known experimental variables and then put to see patterns from which should be able to predict. What you are trying to do is present a whole lot of information and then mathematically develop it in a predictive algorithm, for example heart rate monitoring. We develop predictive algorithms by knowing physiology and putting it into a mathematical database that allows us to look at predictive outcomes … [We arrive at] a mathematical model then how can we model that in an experiment and that is a real challenge.

The following account demonstrates Laura's depth of understanding of how her work with experimental models as well as her critique of the data on which she had based her predictions to rethink her original premise that the fetus and pre-terms would have similar responses to oxygen deprivation. Laura told the story about her discovery that led to a paradigm shift about the resilience of the fetus to oxygen deprivation. This story illustrates how Laura constantly uses the experimental data to interrogate the robustness of the experimental models on which she is working.

> Our hypothesis was based on that there was no difference between the reaction to oxygen deprivation between the fetus and the pre-terms. For a long time we didn't even know if the fetus had the capacity to detect oxygen deprivation and could respond. It was about a paradigm shift that comes back to our perception. If you look at a pre-term baby - newborn baby born at 25–26 weeks instead of 40 weeks. They are so small (500–600 grams) and you look at them in hospital and all you see is fragility and vulnerability and immaturity … so they are not able to cope with any challenge because they are so fragile.

Consequently, she assumed that when she developed an experimental model to monitor the reaction of the sheep fetus to oxygen deprivation, she would need to keep the period of insult short. To her surprise she found that she had to push out the length of time to 30 min in the sheep fetus before she saw the clinical patterns of injury that would be seen with term fetuses after 10 min. Suddenly she realised the paradigm of trauma from oxygen deprivation was different for the fetus as it is living in a very unique environment that is not the same as a pre-term baby. This account of how she discovered this unexpected data when manipulating the model meant that she was able to show the existence of a new information about the the vulnerability of fetuses that could not be equated with a pre-term baby. Such a revision to model design is also a reflection of this scientist's high level of MC because adjustments to the model were based on a paradigm shift of thinking about the vulnerability of the fetus to oxygen deprivation.

Because she looks at the model as an experimental tool that provides knowledge to inform the model to identify conditions for fetal damage in human fetus, this attention and adaption of the model is central to her research.

> You really do have to be constantly looking at your data and what does it tell you and what kind of adjustments do you make to your models. What is the information coming in from the clinical or other experimental models that tell you we should be looking at something … and it is all additive. It is the integration of knowledge

5.6 Summary

When attempting to assess the MC of Laura and her team it is evident that they have a profound understanding of the purpose of these experimental models (that is chronically instrumented fetal sheep) to provide data that can be used for clinical diagnosis of trauma in the human fetus and subsequent treatment of preterm babies.

Although the model fetal sheep provides a physical model upon which experiments can be carried out, she also sees the nature of her models as predictive sets of data that provide guideposts to detection of trauma in the human fetus and pre-term baby. She has a deep appreciation of the role of the model as a tool that can provide data for developing these clinical models. Her understanding of the epistemic issues involved in testing a hypothesis on a fetal model sheep is shown with her discussion about the need to think about the statistical representation of the data she intended to collect and analyse. This research group continually question the validity of their experimental models in representing the human fetus and in the development of a research design that will provide data to fully represent the theories they wish to support. This account of Laura and her research team's thinking about how models provide data demonstrate that modeling was centre stage when these scientists were designing their research. In fact, modeling directed their thinking and reasoning through their forays along new experimental pathways.

5.7 Discussion

5.7.1 *How Important Is it to Learn from Scientists' Modeling Competence?*

At the beginning of this chapter the argument was put forward that an assessment of MC of scientists was at worst impertinent and at best impractical. Furthermore, the author questioned how fruitful would this assessment be to develop the pedagogy to understand the role of models when science is practised.

Instead I would argue that rather than assessing a scientist's MC, providing examples of scientists' model use where the components of the model – that is source and target, their purpose and how they are developed and critiqued – could contribute to students' developing critical scientific literacy about model use by scientists. As Krell, Upmeier zu Belzen, and Krüger (2014) opine, in order to develop students' deep understanding of the nature and role of models in science, they need to be able to recognise examples of model use. These illustrations could show how models are used when building theoretical explanatory constructions or when they are used as research tools in science. It is proposed that these scientists' stories of model use could help students develop a stronger conceptual understanding of modeling as well as enable them to recognise the prevalence of modeling in scientific practice.

Finally stories about scientists developing and using models provide yet another opportunity to show the messiness, creativity and complexity inherent in how science is practised and supports this push for a deeper understanding of the culture of science that was alluded to in Latour and Woolgar's account of *Laboratory Life* (1986).

These scientists have no need for assessment of their model use - instead we can marvel at their expertise as they find their way to the 'truth of the matter'. These stories illuminate the thinking of these scientists and demonstrate the creativity, complexity and deep understanding of how models are used as they practise science.

5.7.2 *Illuminating Scientist's Modeling Competence for the Classroom*

At this point the question needs to be asked – How can a teacher get valid information about scientists' thinking as they use models in their research? Because educational researchers assert that in order to understand the central role of models in science knowledge development it is essential to access how experts use this tool.

Furthermore, if knowing about models and modeling are key features of science then it is important to make accessible some aspect of scientist's business (Coll, France, & Taylor, 2005). A presumption of their business is not just how they use models when doing science but also the social and intellectual circumstances that determine the direction of scientific research (Chap. 4).

But this understanding does not come by creating situations for students to carry out scientific research and expecting them to pick up this expertise explicitly. As Hodson (2014) opines it is better to teach about the Nature of Science explicitly rather than expecting students to pick up how scientists develop scientific knowledge by conducting their own scientific investigations. There is a compelling argument that in order to teach about model use in knowledge development it is important to access the community of scientists so that teachers can provide an entry into the subculture of science.

In this chapter these scientists' narratives have provided a glimpse of the private language and personal experience of science knowledge development that is so different to the public language of science (Hodson, 2014). Grosslight, Unger, and Jay (1991) note that the expertise of scientists are evident when they provide pragmatic responses to issues of model development and implementation. This was very evident in Siouxsie's decision to revert to bioluminescent bacteria when the coloured model bacteria did not provide the contrasting data that she had anticipated. This change in model parameters was a pragmatic solution to an experimental problem because of her expertise in setting up and adapting models that would provide experimental data but would not have appeared in the publication of her work.

Access to scientists is difficult and an ideal situation is for students to be mentored by scientific experts but although such situations are desirable it is not always practical to be part of scientists' decisions during the development and adaptation of their models. Even though it is possible for students to interview scientists about their view of models, their purpose, the types of models they use and if they ever changed their models (Grosslight, 1991), it would be less likely they would be able to pose questions that gave an indication of a scientist's MC let alone develop a scoring system. Instead it could be more informative if students were provided with scientists' examples of level III competence (Chap. 1) with an accompanying explanation.

The need to interact with scientists was realised in New Zealand with the development of the on line Science Learning Hub where scientists talked about their research which was video recorded. In each case a transcript was provided. Examples of these resources are provided as follows:

- A scientist describes the predictive capacity of models. This video allows students to observe a range of scientific models used as research tools[1].
- The building of a climate model was explained using the parallel analogy of mine craft to demonstrate the strength of a model that can be measured by the data base on which it is formed[2].
- A video entitled 'New Zealand's next top model' tells scientists' stories involved in building a more dependable climate change model. This video provides a

[1] https://www.sciencelearn.org.nz/videos/844-models-in-science

[2] https://www.sciencelearn.org.nz/resources/2232-climate-models

critique of the model and could provide data for student critique and discussion about climate change. These examples of level III competence could be used to show how models are developed to test a hypothesis[3].

What is important for students is to have access to scientists' voices as they describe how they develop, critique and adapt models as they develop some understanding of phenomena. Such narratives provide some insight into an expert's thinking or MC but more importantly they provide an example of the private language of personal experience as they build knowledge rather than the factual but flavourless public language of science (Hodson, 2014).

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[3] https://www.nzgeo.com/stories/esm

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