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The Impure Nature of Biological Knowledge and the Practice of Understanding

This chapter offers an analysis of understanding in biology based on characteristic biological *practices*: ways in which biologists think and act when carrying out their research. De Regt and Dieks have forcefully claimed that a philosophical study of scientific understanding should 'encompass the historical variation of specific intelligibility standards employed in scientific practice' (2005, 138). In line with this suggestion, I discuss the conditions under which contemporary biologists come to understand natural phenomena and I point to a number of ways in which the performance of specific research practices informs and shapes the quality of such understanding.

My arguments are structured in three parts. In Section 1, I consider the ways in which biologists think and act in order to produce biological knowledge. I review the epistemic role played by theories and models and I emphasise the importance of embodied knowledge (so-called 'know-how') as a necessary complement to theoretical knowledge ('knowing that') of phenomena. I then argue that it is neither possible nor useful to distinguish between basic and applied knowledge within contemporary biology. Technological expertise and the ability to manipulate entities (or models thereof) are not only indispensable to the *production* of knowledge, but are as important a *component* of biological knowledge as are theories and explanations. Contemporary biology can be characterised as an 'impure' mix of tacit and articulated knowledge.

Having determined what I take to count as knowledge in biology, in Section 2 I analyse how researchers use such knowledge to achieve an understanding of biological phenomena. My interest lies in the activities through which researchers achieve understanding: that is, in the role of human agency in creating, applying and interpreting biological knowledge to comprehend the world. I present a view of scientific understanding as a cognitive achievement of individual biologists that results from their ability to interact with (models of) phenomena and from their training and participation in specific research communities. To obtain understanding of a given phenomenon, biologists need to exercise specific *epistemic skills* and *research commitments*, which allow them to materially intervene on and reason about the world. Understanding can only be qualified as 'scientific' when obtained through the skilful and consistent use of tools, instruments, methods, theories and/or models: these are the means through which researchers can effectively understand a phenomenon as well as communicate their understanding to others.

In Section 3, I conclude that there are different ways in which biologists can understand a given phenomenon, depending on which skills and commitments they are able to muster in their research. The quality of biological understanding obtained by an individual depends on her capacity to perform some of the several activities that, together, constitute biological knowledge.

1. The Impure Nature of Biological Knowledge

Explaining By Intervening: Theories and Models in Contemporary Biology

Biology is growing increasingly disunified. Biological research is fragmented into countless epistemic cultures, each with its own terminologies, research interests, practices, experimental instruments, measurement tools, styles of reasoning, journals and venues.[i] These cultures are typically constructed around a specific set of issues, the investigation of which requires training in a series of techniques, software applications and instruments that are regarded as appropriate to this aim.[ii] Within this context, it is not surprising to find that different biological fields provide not only different theories about the same sets of phenomena, but also different *types* of theoretical results, ranging from the mostly descriptive knowledge gathered by experimental or field biologists to the largely speculative claims pursued by theoretical biologists through mathematical reasoning.[iii] The knowledge produced by the epistemic cultures engaging in biological research takes various forms, ranging from of a mechanistic, narrative, functional or causal type to mathematical equations, descriptions, representations and categorisations of phenomena. Researchers are not divided as to which type of approach is most informative or correct. More often than not, it is acknowledged that different types of theories can each have *relative significance* towards understanding a given phenomenon (Beatty 1997, S433). As highlighted by Longino (2001) and Mitchell (2003), this pluralism in theoretical approaches is more conducive to the development of biological knowledge than a more uniform landscape, centred on a few unifying laws, would be.

Notably, theoretical results are often expressed and used by researchers in forms other than the propositional statements contained in an explanation. Apart from symbolic representations (such as mathematical equations), we find diagrams, photographs, maps and various kinds of three-dimensional objects playing important roles not only in the context of discovery, but also in the expression and justification of biological knowledge. Biologists refer to these representational tools as *models* of biological phenomena.[iv] The philosophical position that most closely accounts for biologists' eclectic views on models was put forward in 1999 by Morgan and Morrison, according to which a model is defined not by its physical features, but by its epistemic function as a 'mediator' between theories and phenomena. Models represent phenomena (through processes including idealisation, abstraction and analogy) in ways that allow scientists to investigate them. Their representational value depends on their material features as well as on the interests and beliefs characterising the research context in which they are used (Morgan and Morrison 1999, 27). Model-based reasoning, broadly defined as the use of representational tools towards gaining epistemic access to natural processes, is widely recognised as playing a crucial role in the production of scientific knowledge.

How precisely do biologists reason through models? The answer to this question comes from studies of research practice in various biological disciplines, which emphasise that model-based reasoning involves the manipulation of models, that is the possibility to modify them so as to fit different research contexts.[v] Models are tailored to pursuing specific research purposes, which can vary depending on changes in the features of the phenomena to be investigated as well as changes in the material, social and institutional settings of the researchers involved.[vi] Good models are ones that can be *used* by those researchers to fulfil those goals in ways deemed appropriate by the relevant research communities. If a researcher is unable to use a model because she lacks the relevant skills, it will not matter that the model could in principle be useful to her investigation: it cannot be used, and therefore cannot prove useful towards her research.

Consider the case of research on model organisms. The worm *C. elegans*, the fruit fly *Drosophila melanogaster*, the plant *Arabidopsis thaliana* and the mouse *Mus Musculus* are protagonists of experimental research in various fields, from molecular biology to immunology, physiology and ecology. Biologists are aware of the limitations imposed by the use of very few species as representatives of the immense variety of existing organisms: there is a high degree of arbitrariness in assuming that facts discovered through experiments on mice (such as susceptibility to chemicals) can hold for species as different as monkeys or humans. Yet, the preference for using a small set of model organisms as models of the whole of organic life remains largely unquestioned. This is because there are substantial advantages to focusing research efforts on the same organism.[vii] Not only do biologists come to accumulate a great deal of data about its structure and functioning: the very quality of those data is enhanced by the possibility of devising measuring instruments and procedures that are finely tuned to study precisely that organism. The model organisms thus selected become models of other life forms. Limiting the number of models makes it easier to focus on how to use them: and indeed, biologists keep improving their ability to intervene on the selected model organisms in the laboratory. This strategy is so productive as to trump biologists' worries about the extent to which these organisms actually embody biodiversity.

‘Using’ a model can involve straightforward manipulation, as in the case of the handling of actual specimens or cell cultures in the lab, and/or reasoning, as in the case of researchers thinking about a specific description, formula or image as applying to an aspect of the organism. What I wish to emphasise is that, in all cases, biologists reach an explanation for the phenomena that interest them through an intervention on the models used to study the phenomenon in question. This holds whether the phenomenon in question is a concrete object, such as an organism, or an intangible process, such as the dynamics of evolving populations: *explanation in biology is always obtained through direct intervention on models of the phenomenon to be explained*. By ‘direct intervention’, I mean the modification of a model to investigate the biological phenomenon that that model is taken to represent. This can happen through reasoning, as when mentally shifting the terms of an equation used to represent evolutionary dynamics, or through physical movements, as when shifting the order of the balls standing for nucleotides in a plastic representation of DNA’s double helix. Whether expressed in thoughts or gestures, human agency constitutes an inescapable condition for producing explanations of the natural world.[viii]

This position nicely accounts for one of the few characteristics shared by the vast majority of contemporary life sciences. This is the ever-increasing blurring of boundaries between ‘applied’ and ‘pure’ or ‘basic’ research. Within theoretical physics, the term ‘basic research’ has been used to identify ways of producing scientific knowledge that aim primarily at explaining phenomena. Physicists involved in campaigns for the construction of supercolliders, for instance, insist that satisfying human curiosity about how the smallest components of matter look and behave is worth huge investments, no matter what the instrumental value of that knowledge turns out to be. Research of this kind has been contrasted with research explicitly aimed at intervening on natural processes and shaping them at will. Cryptography was born out of the military need to send messages without fear of being intercepted. As such, cryptography can be portrayed as a paradigmatically applied science: it does not produce explanations of natural phenomena, but rather provides the means for efficient and secure communication.

When considering the practices and goals characterising medicine, molecular biology, ecology or evolutionary biology, one finds no obvious distinctions between research aimed at producing ways of intervening in the world and research aimed at producing explanations of biological phenomena. These two types of outcome are part of the same investigation processes and are deeply intertwined with each other. Take biotechnology, which has traditionally been referred to as an 'applied' field because of its explicit focus on enhancing technical expertise and devising methods to apply theoretical knowledge to real processes. A well-known instance of biotechnological research is the development of genetically modified organisms [GMOs], which requires scientists to 'apply' knowledge coming from molecular biology to producing plants and animals with characteristics that are socially and/or economically advantageous. The classification of GMO research as applied does little justice, however, to the contributions to theoretical knowledge by biologists and bioengineers engaging in it. Similarly, the vast majority of supposedly 'basic' molecular biologists explicitly aims to produce techniques through which organisms can be genetically modified. This is because the possibility to intervene on an organism generates opportunities to explain some of its features (as in knock-out experiments, where researchers take away specific chunks of the DNA sequence of an organism so as to gain insight on which genes play a role in the development of which phenotypic traits). At the same time, the ability to explain a given phenomenon is tightly connected with the ability to intervene on it: the production of GMOs is informed by available explanations of how the genome is structured.

Let me emphasise again that I am not contending that biologists aim at intervening and manipulating nature *rather than* at explaining it. I am stressing that scientific efforts at explaining the biological world are *necessarily intertwined* with efforts to intervene in the world.[ix] At least in the case of biology, explaining and intervening are two sides of the same coin, both in terms of the types of knowledge employed in research (i.e., theoretical and applied) and in terms of the goals that research is expected to fulfil (i.e., truthful explanations of natural processes and control over those same processes).

1.2 The Importance of Embodied Knowledge

Already in the 1950s, the intuition that theories and explanations constitute but a part of scientific knowledge was put forward by philosophers Gilbert Ryle and Michael Polanyi.[x] Both men presented systematic reflections on what I shall refer to as *embodied knowledge* – 'know-how' in Ryle's words (1949) and 'personal knowledge' in Polanyi's (1958). They suggested that scientific knowledge never involves merely a theoretical content, that is, *that* which is known (as expressed in propositional or symbolic terms through theories and explanations). It also involves the ability to apply such theoretical content to reality and to interpret it in order to intervene effectively in the world as self-aware human agents.

Polanyi sees such ability as an 'unspecifiable art', which can only be learnt through practice or by imitation, but which is rarely self-conscious, as it needs to be integrated with the performer's thoughts and actions without swaying his or her attention from his or her main goals (1958, 54-55). This is why Polanyi refers to this knowledge as 'tacit', that is, as informing scientists' performance (actions as well as reasoning) in ways that cannot be articulated in words. Polanyi distinguishes between two ways in which scientists can be self-aware: 'focal' awareness, which is tied to the intentional pursuit of 'knowing that'; and 'subsidiary' awareness, which concerns the scientists' perception of the movements, interactions with objects and other actions that are involved by their pursuit. In this view, focal and subsidiary awareness are mutually exclusive; one cannot have one without temporarily renouncing the other. Switching from 'knowing that' to 'knowing how' and back is a matter of switching between these two ways of being self-aware. In fact, his characterisation of know-how as 'subsidiary awareness' relegates this type of knowledge to a secondary position with respect to 'knowing that' (1958, 55). The acquisition of theoretical content constitutes, for Polanyi, the central focus of scientists' attention. Tacit knowledge makes it possible for scientists to acquire such theoretical content, but it is not valuable in itself: it is a means to a (theoretical) end.

While drawing inspiration from Polanyi's emphasis on tacit expertise, I do not think that his hierarchical ordering of types of knowledge ('knowing how' being subsidiary to 'knowing that') does justice to the intertwining of 'knowing that' and 'knowing how' that characterises biological research. Polanyi bases his reflections on the study of physical chemistry – and indeed, it might be that some chemists value theoretical knowledge more highly than the practices and skills used to construct it. Within most of biology, however, the development of skills, procedures and tools appropriate to researching specific issues is valued as highly as – or, sometimes, even more highly than – the achievement of theories or data. The evolution of tools and procedures (as in the case of modelling) is not only crucial to furthering theoretical developments: it constitutes an important research goal in its own right.[xi]

On this point, Ryle proves more accommodating. His analysis of the distinction between 'knowing that' and 'knowing how' does not assume either type of knowledge to be predominant over the other. This is due to an underlying difference between his outlook and Polanyi's. While the latter thinks of the distinction as descriptive, thus presenting the two types of knowledge as actually separate in practice, Ryle presents the distinction as a purely analytic tool with no descriptive value. Indeed, he refers to the idea of an actual distinction between 'knowing how' and 'knowing that' as a false 'intellectualist legend': 'when we describe a performance as intelligent, this does not entail the double operation of considering and executing' (1949, 30). Also in contrast to Polanyi, Ryle defines 'knowing how' as involving both intentional actions and unconsciously acquired habits. In fact, he prefers an intelligent agent to avoid as much as possible the enacting of habits:

> 'to be intelligent is not merely to satisfy criteria, but to apply them; to regulate one's actions and not merely to be well regulated. A person's performance is described as careful or skilful, if in his operations he is ready to detect and correct lapses, to repeat and improve upon success, to profit from the examples of others and so forth. He applies criteria in performing critically, that is, in trying to get things right' (1949, 29).

Ryle does not specifically apply his account to the case of scientific knowledge. Nevertheless, his characterisation of agents 'trying to get things right' by iteratively improving their performance fits my characterisation of biologists' practices and interests. As I illustrated, biologists do learn to use a variety of tools in order to pursue their intellectual interests. They need to keep improving their ability to handle models and instruments, so as to reach their goals. In Morgan's words,

> 'learning from models happens at two places: in building them and in using them. Learning from building involves finding out what will fit together and will work to represent certain aspects of the theory or the world or both. Modelling requires making certain choices, and it is in making these that the learning process lies' (Morgan and Morrison 1999, 386).

The function of models is not exhausted by their usefulness as thinking tools: they are tools for acting as well as for thinking. Thus, the knowledge acquired by a biologist successfully pursuing a research project encompasses both some results (a theory, a set of data or a taxonomical system) and the procedures needed to develop, interpret and reproduce those results. A biologist is not born with the ability to perform the modelling activities required by his research. The skills and expertise enabling him to perform these activities are important products of his work, in the same way as theoretical results are. In fact, as I shall argue below, understanding those theoretical results becomes very difficult without reference to the know-how acquired via relevant research experience.[xii]

On the basis of these considerations, I characterise biological research as involving two types of knowledge, which are closely intertwined and virtually inseparable in practice, but which it is useful to distinguish analytically. The first type includes what is typically characterised as the articulated content of knowledge, that is what we regard as facts, theories, explanations, concepts concerning phenomena that are available independently of specific procedures or ways of acting. Access to cell theory and relevant data about cellular organisation, for instance, can be obtained without any expertise in cell biology or experimental research. I shall refer to this type of knowledge as *theoretical knowledge*.

The second type is what I call *embodied knowledge*. This is the awareness of how to act and reason as required to pursue scientific research. This awareness is essential for biologists to intervene in the world, improve their control over phenomena and handle the representations made of those phenomena. Embodied knowledge is expressed through the procedures and protocols allowing scientists to intervene on the entities and processes of interest; the ability to implement those procedures and modify them according to the research context; the acquired skill of handling instruments and models; the perception, often based on the scientists' experience in interacting within a specific space[xiii], of how to move and position oneself with respect to the models and/or phenomena under study[xiv]; and the development of methods allowing to replicate experimental results.[xv]

I thus posit that biological knowledge has a dual nature, encompassing a theoretical and an embodied component. This follows from the recognition that, in biology, explaining goes hand in hand with intervening. Effective agency improves not only biologists' ability to control their environment, but also their capacity to reason, abstract and theorise. Further, this position accounts for the impossibility to distinguish between basic and applied research in contemporary biology. Against the portrayal of biology as a 'pure' science devoted to acquiring theoretical knowledge of living organisms, I propose to view biology as an 'impure' mix of tacit and abstract, local and general, basic and applied knowledge, whose aim is at once to explain and control nature.

2. Understanding in Biology

2.1 A Matter of Skilful Agency

My view on biological knowledge is very different from the one offered by Carl Hempel, who tried to formalise scientific knowledge by emphasising the axiomatic formalisation of its theoretical results (as Ryle and Polanyi would put it, its 'knowing that' dimension). Hempel classified understanding as a by-product of scientific explanations, thus implying that possessing explanations automatically leads to understanding the phenomena to which those explanations apply (1965, 337). In other words, Hempel claimed that access to theoretical knowledge is a sufficient condition for the understanding of that knowledge and of its applicability to real processes: all one needs to acquire understanding is to consult scientific explanations of the phenomena of interest.

Hempel is right to point out that access to theoretical knowledge does not, per se, imply recourse to embodied knowledge. Scientific theories express the analytic concepts and categories employed in the study of phenomena through specific formulations, which can be propositional (as in a textbook explanation), symbolic (as in mathematical equations) or even pictorial (as in the depiction of a biological mechanism). These formulations can be independent of the use of models to develop and study them, as well as of knowledge about how to apply the theories. In this sense, theoretical knowledge can thus indeed be possessed without recourse to embodied knowledge. Using theoretical knowledge to understand natural phenomena is, however, a different matter. Understanding phenomena by reference to theories and explanations requires some level of know-how about how those theories and explanations apply to reality - such as the assumptions and models that have been employed, the goals characterising the context in which theories were produced, and so on. The individual in the process of acquiring understanding needs to be able to intertwine her material experience of the phenomenon (her observations and experimental interactions with it) with a theory-informed interpretation of that same phenomenon. Understanding natural phenomena by means of theoretical knowledge does require some embodied knowledge; and, vice versa, embodied knowledge needs to be coupled with theory-informed interpretations to provide understanding. To capture this insight, I define understanding as *the cognitive achievement realisable by scientists through their ability to coordinate theoretical and embodied knowledge that apply to a specific phenomenon*.

By the verb 'coordinate', I refer to the strategies that a scientist can learn to use in order to (1) select beliefs, thought processes and experiences that are *relevant* to the phenomenon in question and (2) *integrate* these components with the goal of applying them to the phenomenon.[xvi] Modelling is not the only strategy used to gathering scientific understanding (reflection, observation or taxonomic exercises are good examples of other such strategies). Still, I emphasise modelling here insofar as it is a prominent activity in contemporary biology as well as a good exemplification of the means by which a coordination of knowledge that is relevant to a specific phenomenon can be achieved.

Take again the case of model organism research. Already since a few years, bioinformaticians are collecting data concerning the most prominent model organisms (including Arabidopsis, C. elegans and Drosophila) into large databases, which can be accessed by biologists across the globe. The purpose of these databases is to facilitate the retrieval of available knowledge about these organisms, so as to allow biologists to integrate the insights that they gain from their own research with the understanding acquired by others. Notably, these databases make abundant use of digital models (pictorial representations of varying degree of abstraction, depicting entities as disparate as cells, metabolism and gene expression) and even simulations (of processes such as flowering).

To enhance biologists' understanding of the information that is provided, the curators of these databases do not consider it sufficient to provide a text describing what is known about a particular biological process together with the relevant experimental data. Curators found that biologists can better assess the significance of those data and descriptions when they are directly related to the components of the organism that they are taken to provide evidence for – for instance, by means of images.[xvii] These images, which some researchers call 'virtual organisms', constitute models with which biologists can work. By tinkering with the images, modifying parameters and comparing how different datasets fit the models, researchers coordinate their theoretical knowledge (e.g. of the chemical composition of mRNA, the mechanisms through which mRNA travels across the cell and the available datasets documenting this phenomenon) with their embodied knowledge (e.g. of what mRNA actually looks like under the microscope and how those datasets are produced), thus obtaining some understanding of processes such as gene expression.

Even more remarkably, the majority of experimental biologists that use databases insist on being able to interact not only with virtual representations of organisms, but also with actual specimens. This is because physical interaction with samples of the phenomena in question provides different information from interaction with digital models: particularly, the embodied knowledge acquired through the manipulation of a plant or a fruit-fly is not the same as the embodied knowledge derived by interacting with images of their metabolic cycle. Laboratory specimens offer countless possibilities for exploration and surprising results.[xviii] Most importantly, they offer the possibility to match the researcher's sensory experience of a phenomenon (and of the system in which the phenomenon manifests itself) with her hypotheses and background knowledge. This is another example of the process that I wish to capture through the notion of 'coordination'.[xix]

It will be clear by now that, in my view, understanding a claim or explanation is a largely subjective matter. Understanding is not an attribute of knowledge itself, which can be measured quantitatively (as in 'how much do you understand?'). Rather, it is a cognitive achievement that is acquired by individuals in a variety of ways and that can therefore take different forms depending on the instruments that are used to obtain it. In the case of biological understanding, the quality of the understanding displayed by a researcher will depend on his or her acquisition of appropriate background knowledge *as well* as expertise in handling the instruments, models and theories that make it possible to produce and apply any scientific explanation. Importantly, both types of expertise can only be obtained through *participation and training in one or more scientific communities*. It is indeed important to keep in mind that scientific understanding is not the result of mere individual introspection. Its features are shaped by the necessity of intersubjective communication. The understanding acquired by one researcher will not be accepted as a contribution to science unless she is able to communicate their insight to her peers, so as to make it vulnerable to public scrutiny and evaluation. Individual understanding becomes scientific only when it is shared with others, thus contributing to the growth of scientific knowledge and partaking in the rules, values and goals characterising scientific research.

I do not wish to argue that individuals can disseminate their understanding of a phenomenon in an unmediated, direct way – for instance, by talking to other individuals. This position would be paradoxical vis-a-vis my definition of understanding as the cognitive achievement of individuals, based at least in part on knowledge that cannot be articulated. I propose that individuals possessing a specific understanding of a phenomenon enhance other individuals' chances of acquiring it in an indirect manner: that is, by constructing tools (including models, explanations, experimental set-ups and materials) that might enable other individuals to experience the same kind of understanding. This indirect sharing of understanding characterises both the acquisition and the dissemination of understanding in scientific communities. On the one hand, biologists seeking an understanding of a phenomenon are required to learn as much as possible from similar efforts by other scientists, so as to use the understanding accumulated by others as a vantage point for starting their own research. On the other hand, biologists who acquire new understanding of a phenomenon are required to contribute to the body of theoretical and embodied knowledge available on that phenomenon in ways that will help other scientists acquiring the same insight. The social processes through which biological understanding is acquired and disseminated have a strong impact on the features of such understanding.[xx] A biologist's training and professional life constitute experiences that are highly efficient in enabling her to understand a series of phenomena in a number of specific ways. In what follows, I focus specifically on what I call *epistemic skills* and on their relation to *research commitments* as means to obtain understanding.

2.2 Epistemic Skills and Research Commitments

Prima facie, epistemic skills may be broadly defined as the abilities to carry out a number of activities in order to increase one's understanding of reality. They may be partly innate, such as the skill of drawing an object (which depends to some degree on the talent of the individual attempting such action), yet they are most often acquired through the imitation of others and/or through experience, for instance by trial-and-error. Skilful actions are instrumental in the sense of being necessarily *targeted towards* the achievement of a goal, which in the case of epistemic skills is an improved understanding of (some aspects of) reality. At the same time, the notion of skill concerns also the means and manner by which action is undertaken. An action can be judged as skilful even if it does not result in the accomplishment of its intended goal. This is because the successful achievement of an aim involves more factors than just the intentions and ability of the individual acting to that aim: adverse conditions in the environment, bad timing, social context, interference with other individuals' goals and actions – all these factors can influence the outcome of an action, no matter how skilfully that action is carried out.

The assessment of an action as skilful depends as much on the manner in which the action is undertaken as it depends on its effectiveness in achieving the intended goal. Possessing an epistemic skill implies more than the ability to perform an action: it requires performing that action *well*. This means that we need criteria to determine what it means for an action to be well performed. However, these *regulative criteria* are context-dependent and arguably impossible to classify in an analytic fashion. They are dictated by factors as disparate as the nature of the goal to be achieved; the interests of the person performing the action; the social as well as the material context in which the action is carried out; and the tools available to carry out the action. For instance, what counts as adequate actions in designing an experiment on rats depends on: the phenomenon to be explored (e.g. crowding behaviour, which requires a space where rats are kept together, or intelligence, which involves setting up tasks for individual rats to perform); the eventual hypothesis to be tested (if researchers want to prove that 'high population density induces pathologies', they will test rat behaviour in increasingly small communal cages over a long period of time); current regulations for ethical treatment of laboratory animals (and consequently, whether rats are given sufficient food and space to survive); and, last but not least, whether animal ecologists are likely to consider the results of the experiment as representative for the behaviour of rats in the wild.

This extreme context-dependence makes it uninteresting to list regulatory criteria without looking at specific practices. Skilful actions in biological research have only two features in common: (1) they involve the exploitation of tools in a way deemed appropriate to effectively pursue a proposed goal; and (2) judgement on what constitutes an 'appropriate' course of action depends on standards upheld within the relevant social contexts. The tools to be exploited range across models, theories, experimental instruments, features of the environment as well as samples of phenomena themselves, while the relevant social context is constituted by the community of scientific peers in charge of examining the methods and results of any research programme. These insights are captured by the following definition of epistemic skill: *the ability to act in a way that is recognised by the relevant epistemic community as well suited to understanding a given phenomenon.*

I wish to distinguish three types of epistemic skills. *Theoretical skills* involve mastering the use of concepts, theories and abstract models (that is, being able to manipulate various expressions of theoretical knowledge) towards the understanding of a phenomenon. These skills enable biologists to reason through given categories and classification systems according to specific inferential rules, while at the same time judging the validity of those categories with reference to alternative theoretical frameworks. A second type of skills encompasses the *performative skills* enabling biologists to exploit material resources towards the acquisition of biological understanding of a phenomenon. These skills can only be acquired through direct interaction with the environment (including laboratory equipment and specimens). For instance, a biologist can be told how to cultivate a plant so that it develops as required by a specific experimental set-up. The corresponding performative skills, however, are acquired only through practice, that is, by trying over and over again to act in the desired manner, thus gradually adapting movements and sense perception to the tools and materials used in an experiment, as well as to the standards enforced by the research community of interest. After having experienced the results of sowing seeds in the wrong type of soil, with too little or too much humidity and under varying lighting conditions, the biologist will hopefully have acquired the ability to assess the health of a growing plant and thus to produce specimens that fit her needs.

The ability to conform to existing standards can also be seen as an example of the third type of epistemic skill, that is, of the *social skills* denoting the ability of researchers to behave and express their insights in ways that are recognised by their peers or/and other participants in their social context. Social skills such as patience, charisma and self-assurance enable scientists to secure an environment that is suitable to creating tools (models, theories and instruments) that might help others to acquire and exercise the same theoretical and performative skills as the ones exercised by the creators of those tools. Once other researchers are able to interact with phenomena under the same conditions and with the same skills used to acquire a specific type of understanding, they will be more likely to undergo a similar cognitive experience.

Considerable time and effort is invested in learning a set of skills, certainly in the case of most theoretical or performative skills used in contemporary biology. This means that the set of skills available to any one researcher is limited. Biologists bother to learn and perfect skills that, they believe, will help them to pursue their research interests. Trained researchers, who already master several skills, have a strong tendency to develop projects where those skills can be exercised, rather than embarking on projects where (a) they will have to invest time and effort in acquiring new skills and (b) their old skills might prove useless.[xxi] Through acquiring specific skills, researchers become committed to the actions, concepts and research directions enabled by the exercise of these skills. Whether researchers explicitly acknowledge it or not, certain principles, concepts, ways of acting and handling objects become *entrenched* in the practice of researchers engaged in the study of a specific phenomenon. They represent knowledge that is assumed, rather than hypothesised, to be relevant to the study of the phenomenon in question. When this happens, those bits of theoretical and embodied knowledge start to be regarded as a necessary platform to carry out research.[xxii] They become what I shall call *research commitments*, encompassing items as diverse as the theoretical perspective held by biologists; their research goals and interests; their ways to perform research and interpret protocols; and their assumptions about the representativeness of their research materials and the applicability of their results.

Research commitments and epistemic skills are different aspects of the same process. Acting skilfully implies committing to the activities and results that those skills bring forth, while making a commitment to a specific technique or concept requires learning skills adequate to follow up on such commitment. Skills denote the abilities to perform an action in a specific manner; commitments consist of a tendency towards (or preference for) pursuing goals that can be obtained through performing that action. The possession of a skill entails a commitment to exploiting that skill (thus taking advantage of an otherwise useless investment). Similarly, once a commitment is made, it implies learning and exercising skills that are relevant to fulfilling that commitment. This is what makes commitments different from a mere promise or a pledge: they imply, and result from, skilful action.

To highlight the link between skills and commitments, I trace a categorisation of commitments that runs parallel to my categorisation of skills. *Theoretical commitments* are commitments to using or investigating specific concepts, theories and principles. Much has been written about this type of commitments in terms of conceptual biases, theoretical perspectives and background knowledge. *Performative commitments* consist of commitments to specific habits, that is, ways of thinking or moving that become entrenched to a scientist's practice. *Social commitments* apply to the interests and values endorsed by scientists as a consequence of their financial, professional and personal dependence on specific social hierarchies, sponsors or practices. For example, peer review mechanisms engender a series of commitments towards wedding one's work to recognised keywords, the expectations of prospective peers and the content of journals in which one hopes to publish; funding agencies might require scientists to observe specific criteria and/or values in their research; or, scientists working in a context dominated by powerful professors might have to adopt their views to be granted funding for research.

Together, skills and commitments represent two fundamental tools for the achievement of understanding. Commitments guide researchers towards acquiring skills relevant to the pursuit of these commitments. As a result of exercising these skills, scientists become aware of how their experiences, as well as the concepts and tools that they use, fit or challenge available explanations of phenomena. Adherence to commitments and skilful research practices constitute basic conditions under which researchers coordinate theoretical and embodied knowledge towards understanding phenomena.

3. Many Types of Understanding

The prominence of scientists' skills and experiences in achieving coordination between thoughts and actions, conceptual analysis and sense-perceptions, effectively separates the understanding thus obtained from the mere possession of theoretical knowledge in the form of a theory or an explanation. Theoretical knowledge, per se, does not provide biologists with the theoretical and performative skills needed to trace its significance for natural phenomena. In biology, to 'know' implies not only to possess theoretical knowledge, but also to be able to use it towards understanding actual phenomena. The ability to use theoretical knowledge to that aim is granted by embodied knowledge, and particularly by the components of embodied knowledge that I called epistemic skills.

Researchers possess different combinations of skills and commitments depending on the epistemic culture to which they belong, their goals, training and professional experience. Of course, all researchers, no matter what their field and occupation is, possess a minimal amount of theoretical knowledge as well as theoretical commitments to specific concepts and theories guiding their research; and they possess embodied knowledge, in the form of both theoretical and performative skills, as well as performative commitments. Yet, the balance between theoretical, performative and social skills, as well as commitments, can vary. Depending on such variation, there can be different ways to understand the same biological phenomenon. I will now briefly discuss three of them.

The first, or *theoretical understanding*, denotes a situation where understanding of biological phenomena is acquired through recourse to theoretical commitments and skills, with performative skills and commitments playing a subsidiary role. A good illustration for this kind of understanding is provided by population biology, that is, one of the main branches of biology studying evolutionary patterns with the help of mathematical models of populations. In the case of understanding gathered in this field, such as for instance the understanding of the evolving interaction of two populations endowed with different traits, research is accompanied by extensive theoretical commitments: researchers are not questioning what is meant by evolution, how populations and population interactions are characterised, whether traits are inheritable or acquired by nurture, as such assumptions are usually a platform from which they can try to derive results. Similarly, theoretical biologists tend to make strong performative commitments towards specific ways of looking at phenomena, such as diagrammatic or mathematical representations and computer programmes allowing for specific types of simulations (and not others). This is the extent to which such researchers interact with phenomena to be understood: with the help of modelling tools that are conceptually abstracted from the phenomena themselves. Performative commitments and skills are therefore subsidiary to the development of theoretical skills and knowledge: they are not an aim in themselves and embodied knowledge of the phenomena under scrutiny is not valued as a crucial component of researchers' understanding of them.

The second kind of understanding, *embodied understanding*, illustrates the opposite situation: theoretical skills and commitments are used to pursue and develop a set of performative commitments and skills, which constitute the main interest of the researcher. Embodied understanding does not require making substantial theoretical commitments. What is central to it is the ability to intervene in phenomena, rather than to explain or predict them. Embodied understanding is geared towards acquiring control over phenomena. The emphasis is on mastering performative skills that will be useful to explore and modify phenomena at will. This does not mean that theoretical skills are absent. In some cases, theoretical skills and commitments might be extensively use to obtain embodied knowledge – for instance, in the biomedical sciences, where an understanding of germ theory, genetics and physiology is crucial to being able to diagnose and treat a patient. Still, doctors rate their ability to manipulate organisms over and above their ability to explain how organisms functions. What they aim for is an embodied understanding of human beings, which can guide their actions even when they have no idea of why or how the processes referred to as 'symptoms' take place.

The third kind of understanding is the *integrated understanding* deriving from a balanced exercise and coordination of theoretical and embodied knowledge. Neither theoretical nor embodied knowledge are given a privileged role in the understanding of a phenomenon. Rather, researchers are interested both in acquiring a theoretical interpretation of a phenomenon and in obtaining tools and methods that will enable them to match such theoretical interpretation to the actual features of the phenomenon. To this aim, the embodied knowledge used to acquire this type of understanding includes both theoretical and performative skills: researchers exercise their ability to reason as much as their ability to observe and/or intervene on the phenomena under scrutiny.

Each type of understanding is suited to different research contexts, since the quality of understanding acquired by biologists depends largely on their research settings and goals. For instance, theoretical biologists need to concentrate all their skills and resources on acquiring theoretical interpretations of phenomena. This means committing to using mathematical modelling, that is, models with high explanatory power but little empirical content. Arguably, this leads to gaining insights that might not have been obtained if biologists insisted on making empirical sense of their findings throughout their research. It thus seems entirely justified to regard theoretical understanding as the most useful kind of understanding in theoretical biology. Another example is the field of natural history, where researchers commit to accumulating detailed knowledge about the morphology of as many species as possible. They thus acquire embodied understanding of what organisms look like, where they can be found and how they should be spotted, kept and eventually embalmed. It does not matter to them that the skills and commitments of natural historians greatly limit their theoretical understanding of the differences among organisms (and the causes of such difference): for their research purposes, the best understanding of organisms is embodied rather than theoretical.

Do theoretical, embodied and integrated understanding then have the same epistemic value in biology? I think not. From a normative viewpoint, integrated understanding constitutes the most desirable form of understanding biological phenomena, since it involves considering theoretical and embodied knowledge as equally relevant to understanding a phenomenon. As I have claimed in Section 1, biology is about the exploration *as well as* the analysis of phenomena: researchers who understand a phenomenon in one of these two ways should ideally strive to understand it also in the other, thus balancing the amount of theoretical and embodied knowledge used to this aim and acquiring as rich as possible an understanding. The theoretical understanding of evolving systems acquired by theoretical biologists could actually be viewed as very partial, given that these researchers often have no idea of how their results could apply to actual phenomena. Reliance on mathematical models often implies losing the (embodied) sense of how the results acquired through these models and the parameters used therein could be matched to observations, measurements, statistics and other empirical data, since what is taken to define an organisms or a population in the models differs substantially from the complex features of actual organisms and populations. Similar problems plague the field of natural history, which has lost much of its 18th century attractiveness precisely because it does not provide ways to make theoretical sense of the observed differences among species. In both examples, researchers seeking *either* theoretical *or* embodied understanding seem to be missing out on something important. In Hacking's words, what biologists should strive for are ‘happy families, in which theory and experiment coming from different directions meet’ (1983, 159).

Whether biologists can actually pursue integrated understanding in practice, given the disunity and extreme specialization characterizing contemporary research, is a matter of dispute. Cutting-edge fields such as system biology, bio-ontology and evolutionary-developmental biology are attempting to build tools that might indeed enable biologists to better coordinate their theoretical and embodied knowledge of the natural world (such as databases and *in silico* experiments). Philosophers interested in the practice of understanding will hopefully be in a position to contribute to the success of these efforts.

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[i] Dupré (1993), Rosenberg (1994), Mitchell (2003) and Winther (2006), among others, propose careful analyses of these elements.
[ii] For the mechanisms through which specific tools come to be regarded as indispensable to an epistemic culture, see Knorr-Cetina (1999) and Galison (1997).
[iii] Mitchell (2003) critically surveys different notions of biological theory formulated by philosophers of biology.
[iv] The collections of essays edited by de Chardaverian and Hopwood (2004), Laubichler and Müller (2007) and Suarez (2007) provide examples of the many types of models used to gain knowledge about natural phenomena. See also part two of this volume.
[v] See references in footnote iv for examples.
[vi] Mattila (2006) discusses the significance of tailoring models.
[vii] On the advantages of model organism research, see also Ankeny (2007) and Leonelli (2007a, 2007b).
[viii] A similar point is made in Hacking's 1983 defence of the significance of manipulating entities in science, even if his notion of intervention, focusing on experimental interference with phenomena, is narrower than the one I propose.
[ix] In his (2003) manipulationist account of causal explanation, Woodward takes a view that is more general than mine – in the sense of applying to causal explanation in all sciences – but also more restrictive, insofar as it is limited to causal explanations. My approach is meant to hold for all types of explanations, including functional and

nomological, while I remain agnostic on whether this could apply to sciences other than biology. Verifying this latter claim would require extensive comparative analyses among the sciences, which is beyond the scope of this chapter.

[x] This is leaving aside the contributions to the study of agency in science made by scholars focused on experimentation (e.g. Gooding [1990] and Radder [2003]) and the early pragmatists (particularly William James, Charles Peirce and John Dewey).

[xi] See Rheinberger (1997) and Suarez (2001) about the role of instruments and techniques in shaping the experimental culture in molecular biology; and Gilbert (1991) on the paradigm shift occasioned in biology by the advent of new data-producing techniques (such as sequencing) and bioinformatic resources (such as internet databases).

[xii] Acknowledgements of the tight connection between learning and the material manipulation of objects have a long history and are increasingly accepted in cognitive science. Indicative of this trend is the recent focus on 'embodied cognition' – see for instance Anderson (2003) and references therein.

[xiii] Latour influentially argued that any site of scientific research becomes a laboratory setting (Latour 1987).

[xiv] Myers (forthcoming).

[xv] Hans Radder (2006) convincingly argues that the development of methods to replicate experimental results is a necessary step towards developing theories.

[xvi] In a similar vein, Galison uses the expression 'coordination of action and belief' to describe interactions between experimentalist and theoretician culture in physics (1997).

[xvii] For curators' reflections on this point, see Huala et al (2001).

[xviii] On the importance of surprises in exploratory modelling, see Morgan (2005).

[xix] Experimentation is a very efficient way to coordinate theoretical and embodied knowledge. It has become a trademark scientific activity at least in part because of that. However, I do not take it to be the only way to achieve such coordination, as shown by my first example about the manipulation of digital images.

[xx] This important point is developed in Leonelli (2007b).

[xxi] Under pressure to produce as many short-term results (publications or patents) as possible, researchers are rarely given time and funding to acquire new skills without being able to prove that their usefulness.

[xxii] Elihu Gerson remarks that: 'our tentative alliances [with phenomena] become stronger as they are used successfully as tools and materials in other projects. It is at this point that our theories become 'facts', firm commitments to act in a certain way' (1998, ch.2, 13). Note again the similarity to Hacking's formulation of entity realism, where the ability to manipulate an unobservable entity in the laboratory constitutes a criterion for believing in the existence of that entity (1983, 265).