Integrating History and Philosophy of the Life Sciences in Practice to Enhance Science Education: Swammerdam's *Historia Insectorum Generalis* and the case of the water flea

Abstract: Hasok Chang (*Science & Education* 20: 317-341, 2011) shows how the recovery of past experimental knowledge, the physical replication of historical experiments, and the extension of recovered knowledge can increase scientific understanding. These activities can also play an important role in both science and history and philosophy of science (HPS) education. In this paper I describe the implementation of an integrated learning project that I initiated, organized, and structured to complement a course in history and philosophy of the life sciences (HPLS). The project focuses on the study and use of descriptions, observations, experiments, and recording techniques used by early microscopists to classify various species of water flea. The first published illustrations and descriptions of the water flea were included in the Dutch naturalist Jan Swammerdam's (1669) *Historia Insectorum Generalis*. After studying these, we first used the descriptions, techniques, and nomenclature recovered to observe, record, and classify the specimens collected from our university ponds. We then used updated recording techniques and image-based keys to observe and identify the specimens. The implementation of these newer techniques was guided in part by the observations and records that resulted from our use of the recovered historical methods of investigation. The series of HPLS labs constructed as part of this interdisciplinary project provided a space for students to consider and wrestle with the many philosophical issues that arise in the process of identifying an unknown organism and offered unique learning opportunities that engaged students' curiosity and critical thinking skills.

1 Introduction

Philosophy of science is typically thought of as a subject that asks very broad, general, and abstract questions: What is scientific knowledge and how do we get it? What methods of investigation should we use? What kinds of things are in the world? and how are they organized? Lab and field sciences investigate more narrowly defined, specific, and concrete questions. Philosophical investigations appear to have few limits—perhaps just the accessibility of texts and the language and comprehension of the investigator. Restrictions are numerous in scientific investigations. The appropriateness and availability of reliable methods; the cost of and access to required equipment and lab space; the viability and fecundity of research organisms; and the likelihood of finding a result in the time allotted all limit the scope of possible experimentation. This seems to present a substantial challenge for anyone seeking a way to integrate the two.

Bringing together the history of science, the philosophy of science, and scientific practice, Hasok Chang (2004, 2009) suggests this integration is not only possible but provides an exciting pathway to interdisciplinary research that can generate new knowledge. He calls this type of integrated investigation "complementary science". Complementary science investigates questions that are not being explored by practitioners of the specialist science at present. It interrogates what is currently accepted as knowledge, the reliability and accuracy of scientific instruments, and standard operating procedure in the specialist science. These kinds of investigation are not typically seen as appropriate areas of investigation for the specialist and are not the kinds of research questions that are pursued or indeed funded. Critical questioning of accepted knowledge and practice is avoided in part due to the nature of specialist science, as a *specialist* discipline. Specialists do not ask the more general questions that examine the foundations of the knowledge and tools that they rely upon for their investigations. *That* specialists do not ask such questions does not mean that these represent an area of research not worth investigating. Certain assumptions must be made allowing scientists to get on with their research. As a consequence, some avenues of investigation are left unexplored. These questions are not neglected because they are uninteresting. They are neglected so that specialists can get on with the project of *doing science* (Chang 2009).

However, Chang (2004, 2009) argues that this lack of questioning may actually represent a loss of knowledge and suggests that historians and philosophers of science are well-placed to explore and investigate these neglected but scientifically interesting questions. He explores how the recovery of past experimental knowledge, the physical replication of historical experiments, and the extension of recovered knowledge can enhance scientific knowledge. In a paper recently published in this journal, Chang (2011) suggests that the complementary science approach to investigation and the use of historical experiments and can improve students' scientific understanding when used in science education. This paper takes Chang's suggestions seriously. In it I describe the implementation of an integrated learning project that I initiated, organized, and structured to complement a course in history and philosophy of the life sciences (HPLS).

2 Biological classification: problems and prospects

In pursuit of a different path of philosophical investigation suitable for undergraduate students, I began thinking about how to adapt Chang's suggestions to my own disciplinary and pedagogical interests in history and philosophy of biology. With research interests in the history and philosophy of chemistry and physics, Chang describes his historical experiments in boiling water and electrochemistry to explain and exemplify complementary experiments and the complementary mode of scientific investigation (Chang 2007, 2011). Keen to construct a project that dovetails my own research areas and those central to my teaching in HPLS, I decided that a project that enables students to explore first-hand some of the philosophical problems surrounding biological classification would contribute significantly to both.

Biologists and philosophers have long discussed the nuanced set of problems surrounding the definition and conceptualization of species frequently referred to as "species concepts". At last count there were 27 different species concepts (see Wilkins 2011).[1] Discussions of species concepts often focus on the problems concerning how to define the category of *species*—widely referred to in both biological and philosophical writings as the "species problem" (Claridge, Dawah, & Wilson 1997; Wilson 1999; Richards 2010). While exploring these ongoing debates within the biological and philosophical research is no doubt a valuable enterprise, my aim was to construct a project that would allow biology and philosophy undergraduates to actively engage in historical and philosophical research in biological classification that confronted them with these theoretically and conceptually challenging problems.

[1] Wilkins (2011) suggests that these 27 different species concepts could ultimately be sorted into seven different types of definitions of "species": asexual species, reproductively isolated sexual species, ecological niche occupying species, species lineage, genetic or gene pool species, morphological species, and taxonomic species concepts. Monists argue that there is actually just one *real* concept of species, whereas pluralists argue that there must be at least two, and eliminitivists (see Hey 2006) argue that there are none.

To do this, I designed a series of complementary experiments that were incorporated into the HPLS course.[2] These facilitated the kind of philosophical thinking about conceptual problems of classification that challenged students and made use of both their lab skills and philosophical skills of analysis.[3]

In the Autumn of the first year (AY2010-2011) of my current post as an assistant professor specializing in philosophy of biology and knowing that one of the courses I was responsible for (in the Spring semester 2011) was a cross-listed course in HPLS, I began to plan how I could integrate a lab element into my teaching of the course. The HPLS course is a junior-senior level (year 3-4) cross-listed course in philosophy, biology and chemistry. It is required for both philosophy majors and science education majors focusing on secondary biology, chemistry and physics education. It is also an elective for other students.[4] Prior to my appointment it had been traditionally team taught by members of the philosophy, biology, and chemistry faculty. I was now solely responsible for it and was given complete freedom to construct and design the course with the support of the cross-listed faculties.

I chose to organize the course around fundamental questions that focused on the nature and development of scientific knowledge and understanding in the life sciences organized in three parts. The focus of the first part of the course is the nature of scientific understanding and how can scientific knowledge be known. It considers the problems that arise when we try to

[2] Critical observation is a central feature of biological investigations focussing on classification (Mayr 1997). Depictions and descriptions of the observed object of research serve as the basis for understanding the categories or kinds of things that are considered to be the subject matter of that discipline (see later discussion contrasting Mayr's (1997) distinction between "what?" questions and "how?" and "why?" questions in section 6: How can HPLS observations and investigations augment science education and scientific knowledge?" Because the project focussed on classification based on observation, Chang's complementary science approach required substantial modification from one that fit the discipline of chemistry and historical experimentation to one that fit the disciplinary interests and knowledge-producing investigative techniques of biological classification. But because microscopic investigations, although not experiments, play an analogous role in biology that experiments play within chemistry—generating specific knowledge about that which is being observed (whether in terms of morphology, behavioural reactions, external or internal structural organization), a complementary approach modelled on Chang's was possible.

[3] In the role of complementary scientist, the HPLS students were directed to observation as the key investigative technique used in knowledge acquisition and generation by the early naturalists. In this way, the aim of the current project was not for them to rely on molecular phylogenetic investigations using current taxonomic techniques that they had used in upper-level university biology courses such as Genetics or Plant Systematics. Within these courses, students use biochemical techniques such as polymerase chain reaction (PCR) as well as the Basic Local Alignment Search Tool (BLAST) to find regions of similarity between genetic sequences. Instead, the aim was to rely on earlier techniques of depiction and description set out within the context of the history and philosophy of the natural sciences and focussing on the investigations of the early microscopists.

[4] The enrolment for the Spring 2011 term included a broad range of subject majors including biology, chemistry, philosophy, psychology, mathematics, and computer science. I set a prerequisite for the course of the completion of 2 lab sciences.

demarcate science from non-science, as well as investigating the structure of scientific revolutions and progress. We read central texts on the problem of induction (Popper 1959), falsificationism (Popper 1963), Kuhnian 'normal science' (Kuhn 1970), science and pseudoscience (Lakatos 1977, Thagard 1978), progress and research programmes (Lakatos 1968), and science and objectivity (Longino 1990). In the second part of the course, students focused on key areas of philosophical discourse within HPNS: reductionism in the special sciences (Fodor 1974), the unity of science thesis (Oppenheim & Putnam1958), explanatory unification (Kitcher 1981), innateness (Griffiths 2002, Samuels 2004), the disunity of science (Dupré 1993, Hacking 1996), and the role of mechanism in science (Machamer, Darden, & Craver 2000). In the final part of the course students focus on how these general issues can be understood within the philosophy of the special sciences, in particular philosophy of biology (Dupré 1981, 1999, 2002), philosophy of chemistry (Chang 2004, 2007, 2009), and philosophy of mind (Clark & Chalmers 1998, Clark 1995). It is in this final third that I integrated historical experiments into the course. Within these, students were able to use the recovery of past experimental knowledge and techniques gained through their philosophical and historical research and actively use these in their observational and experimental investigations in the lab. The organisms that I eventually chose for these HPLS labs were the freshwater microcrustacea of the genus *Daphnia* (order: Cladocera, family: Daphniidae), commonly referred to as "water-fleas".

3 Why *Daphnia*?

Initially described and illustrated by Jan Swammerdam in his *Historia Insectorum Generalis* in 1669, water fleas have been and continue to be extensively studied by scientists, students, and naturalists alike. For decades, water fleas of the genus *Daphnia* have been a popular teaching tool in both high school and university biology labs. Worldwide distribution means that *Daphnia* can be found living in every continent except Antarctica (Lampert 2010). Although widely available through biological supply companies, *Daphnia* are also available in pet shops as live food for tropical and marine fish keepers. But the sheer diversity and abundance of their aquatic environments (wetlands, open lakes, ponds), also makes collection of water fleas both free and easy.

Daphnia are tiny, ranging from 0.5 to 5 mm (Lampert 2010) but they are visible with the naked eye. Their transparent carapace makes *Daphnia* ideal organisms for studying the live functioning and movements of their internal organs. This transparency also allows students and researchers to count daphnid eggs as well as view the young daphnids whilst still in their mother's brood chamber. *Daphnia* reproduce quickly (7-9 days before first brood) and tend to be parthenogenic, but some are cyclically parthenogenic (they reproduce sexually given certain conditions that trigger the production of males) (Lampert 2010).

The ecological endemism and polyphenisms of Cladocera have long been studied. In addition to the pioneering work of Swammerdam, perhaps the most significant contributions to early Cladocera study were the observations and descriptions completed by the Norwegian naturalist, Georg Ossian Sars (1861/1993, 1895) who described and extensively characterized their morphology and ecology. Water fleas respond quickly to environmental changes and variations. Their sensitivity, responses to toxicity, and environmental pollutants means that many species of Cladocera are widely used as model organisms in hydrobiology, limnology, and ecotoxicology research (Cerbin et al. 2010). One of the most widely observed behaviors is diel vertical migration (De Meester 1996) in reaction to detecting chemical cues from predatory fish, Dipteran larvae such as the phantom midge (*Chaoborus americanus*), or adult backswimmers (*Notonecta undulate*) (Hanazoto 1991, Tollrian & Dodson 1998).

The well-documented developmental and phenotypic plasticity of the various species of *Daphnia* mean that it is a frequently discussed exemplar in developmental biology and niche constructionism (Laland, Odling-Smee & Gilbert 2008; Piersma & Van Gils 2010). When hypoxic they turn red (due to an increase in hemoglobin), and many species display combinations of defense mechanisms in response to detecting the chemical kairomone of diverse predators. These include a defensive helmet, a "crown of thorns", elongated head spine, tail spine, thickening of the cuticle, increased body length, and the development of neck teeth.[5] These include but are not limited to *D. magna, D. atkinsoni, D. pulex D. galeata, D. retrocurva, D. ambigua, D. obtuse, D. parvula, D. pulicaria, D. retrocurva,* (Dodson 1989, Boersma, Spaak, & De Meester 1998). Plasticity has also been observed in connection with *Daphnia* behaviour such as migration, phototaxis, and swarming reactions (Kvam & Kleiven 1995) and in

[5] See for example Grant & Bayly (1981), Hanazato (1991), Hunter & Pyle (2004), Krueger & Dodson (1981), and Tollrian (1994).

connection with developmental strategies ensuring fecundity such as increased egg clutches, decreased lipid reserves, and changes in the order of life history stages (Stibor 1992, Pijanowska 1994).

As a highly polyphenic cyclical parthenogen that is fairly easy to culture, reproduces quickly in its ameoitic phase, and is in abundant supply in our university's lakes and ponds, *Daphnia* seemed like an obvious choice for a philosopher of biology with rusty lab skills and a modest research budget.

4 Recovery of lost techniques and methods of classification

A wealth of *Daphnia* research spanning 342 years has produced a substantial store of knowledge concerning its phenotypic plasticity, predator induced behaviours, diel vertical migration, various aspects of its ecology and physiology, as well as its ability to reorganize its life cycle stages (Hunter and Pyle 2004; Cerbin et al. 2010; Lampert 2011). However, the diverse phenotypic, behavioural, life history adaptations, and the strong endemism of some of the species of the genus *Daphnia* also introduce particular challenges to its species classification. Despite frequent use of *D. pulex* and *D. magna* as common research organisms in classrooms around the world and by intensive research by *Daphnia* specialists, the taxonomic status of many species of Cladocera is vague (Korovchinsky 1996). Using a combination of investigative techniques, David Frey (1982, 1986, 1987) showed that the long-held view that Cladocerans were best described as having a cosmopolitan distribution (a common view during the 1950s-1980s[6]) was incorrect and that these groups were in many cases actually intraspecific units and species complexes. Frey (1987) revealed that careful study of Cladocerans required critical assessment of old taxonomic assumptions using new methods of investigations, techniques and approaches including electron microscopy and genetic and molecular analysis. Frey's critical assessment led to the suggestion posed a decade later that "we have to conclude that all identification books are obsolete and even the most recent are already in need of updating" (Korovchinsky 1996: 202). Early work produced insufficient understanding of the diversity of Cladocera and many descriptions incorrectly report taxonomic diversity and redescription of many species has been necessary (Frey 1986, 1987, Korovchinsky 1997). Species diversity of Daphniidae in particular,

[6] See Forro et al (2008) for discussion of the origins of the assumption of cosmopolitanism in Cladoceran species.

and estimates of the number of taxa of Cladoceran species in general, remains the subject of much research. Numerous regional studies have propagated a new set of non-cosmopolitan concepts and methodologies to resolve the species diversity of *Daphnia* populations using molecular markers[7], genetic, and biogeographical data (Adamowicz, Hebert, & Marinone 2004, Nilssen et al. 2007). These focus on the apparent "provincialism" (Coulbourne et al. 1998) or endemism rather than the assumed cosmopolitanism of earlier investigations and suggest that "despite more than 200 years of attention, the taxonomy of this genus is still uncertain" (Adamowicz, Hebert & Marinone 2004). Confusion persists on how best to designate certain particularly unruly groups of related species including the morphologically plastic *D. longispina* complex. Widespread hybridization and morphological plasticity make these nomenclaturally liminal despite Sars' original delimitation of this group in 1861. Revisions to its classification are ongoing as a result of Frey's (1982, 1986, 1987) and others (see for example Nilssen et al. 2007, Petrusek et al. 2008). Despite the use of genetic and molecular data many species classifications of *Daphnia* remain unresolved (Edwards 1980; Schwenk, Ender & Streit 1995; Kotov & Taylor 2010).

In 2011 the genome of *D. pulex* was sequenced and published (Colbourne et al. 2011). The *D. magna* genome sequencing project, now in its fifth year, has compiled a beta gene set (Colbourne 2011). Genomic data has increased our knowledge of these organisms and their possible relatedness with other sequenced model organisms (Edwards 1980; Schwenk, Ender & Streit 1995; Kotov & Taylor 2010).[8] Although frequently overshadowed by genetic data, morphology continues to play a role in *Daphnia* classification and is still accepted as a key feature used in microcrustacea taxonomy despite their heritable polymorphisms, geographic variability, and phenotypic plasticity (Dodson & Lee 2006).

While many mainstream biology textbooks (e.g. Futuyma 2006) continue to characterize evolution as changes in the gene frequency of populations, opponents of this gene-centred view are becoming more numerous. Recognition of the significance of ecologically-induced phenotypic changes such as those of the head and neckteeth of parthenogenetic *Daphnia* have

[7] For example, the 12S mitochondrial marker was used to delimit *D. lacustris* from other *D. longispina* complex (for discussion of the use of this and the ITS molecular marker see Nisslen et al 2007),

[8] Although current techniques used in classification include observations of morphology of waterfleas, these tend to be trumped when used in conjunction with genetic techniques. Genetic techniques are frequently used to make final distinctions necessary to resolve taxonomies (for discussion of the use of genetic investigations see Adamowicz, Hebert & Marinone 2004).

lead to the suggestion by some that a re-synthesis of ecology with developmental and evolutionary biology may be needed (Gilbert and Bolker 2003). Along with this, a more ecologically-sensitive notion of species is also required in order to replace (or at least augment) the current largely gene-centred one (Kendig 2009, 2012).

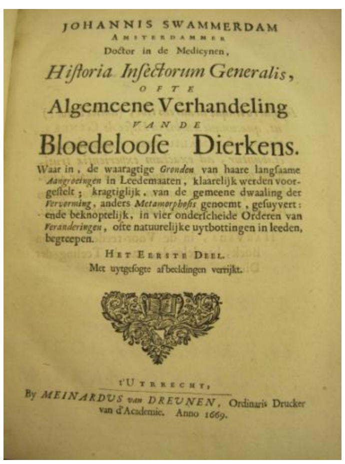
The ecological endemism and phenotypic plasticity of *Daphnia* make it a particularly pedagogically useful model organism for the HPLS lab projects. Observational research and the keying-out of water fleas furnish unique learning opportunities for students to consider and use early pre-Linnaean morphological notions of species classification. And they are ones that may provide further understanding and insight into current classification practices. The morphological and behavioral variations observed within cyclical parthenogens, such as *Daphnia pulex,* which predominantly reproduce asexually (Tollrian and Dodson 1998) are not solely or even perhaps primarily understood in terms of changes in the gene frequency of populations or lineages. As organisms that reproduce cyclically by means of meiotic and ameoiotic reproduction, their lineage resembles that of an asexually reproducing clone during cycles of ameoitic reproduction. Organisms reproduced in this cycle are genetically identical to each other. This means that if there is wide morphological variability among organisms this may be due to other factors besides genes.

What initially made *Daphnia* exciting research subjects for this project was their long (but partially forgotten) history of unruly and unresolved taxonomy. Although *Daphnia* continue to be used as popular model organisms in a number of research fields and as a frequent pedagogical tool in university biology labs, the discussion of the early history of *Daphnia* research and classification is, at best, sparse. Swammerdam's contributions are occasionally mentioned but rarely discussed even in limnology and ecotoxicology textbooks. Photographs of the differing head shapes of *Daphnia* are popular exemplars used in textbooks on developmental biology but tend to be unaccompanied by any extended discussion. *Daphnia* are only given a brief mention in Mary Jane West-Eberhard's 749-page tome, *Developmental Plasticity and Evolution* (West-Eberhard 2003).

In one of the longest and most referenced recent historical reviews on *Daphnia* classification, there is a mere two paragraphs detailing the contribution of naturalists from 1669-1763 (Korovchinsky 1997). Winfried Lampert (2011) takes just a short paragraph to discuss this same time period in a section entitled "the long history of a model organism" in his otherwise comprehensive 250-page volume *Daphnia: Development of a Model Organism in Ecology and Evolution*. Background research undertaken during the beginning and throughout the project indicated this abridgement of history to be very common with very few exceptions (notably Fryer 2008).

Researching the history of *Daphnia* classification proved to be a challenge. Although some secondary texts, much current research, and some historical reviews were widely available the primary texts were not—namely Swammerdam's *Historia insectorum generalis* / *Algemeene verhandeling van de bloedeloose dierkens*.[9]

After an extensive search, the original texts of Swammerdam were found to be available in the rare books room at the Linda Hall Library of Science, Engineering and Technology in Kansas City. With the kind help and assistance of the library staff, the students and I were able to carefully study the illustrations and descriptions from each edition of Swammerdam's *Historia Insectorum Generalis* beginning with the original work from 1669.[10]


JOHANNIS SWAMMERDAM
AMSTERDAMMER
Doctor in de Medicynen,
Historia Insectorum Generalis,
OFTE
Algemeene Verhandeling
VAN DE
Bloedeloose Dierkens.
Waar in, de waaragtige *Gronden* van haare langsaame *Aangroeingen* in Leedemaaten, klaarelijk werden voorgestelt; kragtiglijk, van de gemeene dwaaling der *Vervorming*, anders *Metamorphosis* genoemt, gesuyvert: ende beknoptelijk, in vier onderscheide Orderen van *Veranderingen*, ofte natuurelijke uytbottingen in leeden, begreepen.
HET EERSTE DEEL.
Met uytgesogte afbeeldingen verrijkt.
t'UTRECHT,
By *MEINARDUS van DREUNEN*, Ordinaris Drucker van d'Academie. Anno 1669.

[9] An English translation was published posthumously in 1758 as *The Book of Nature*.
[10] Swammerdam drew his own illustrations in the original 1669. Although utilizing the English translation for the text, we relied on Swammerdam's original illustrations for our studies and investigations in the lab. We noted slight but distinct differences in the illustrations posthumously published in the English edition in 1758. Interestingly, the publisher did not include Swammerdam's original 1669 drawings in the English edition but instead hired an illustrator to redraw Swammerdam's original illustrations. These redrawings modified Swammerdam's original illustrations making them arguably less accurate and more stylized (for and interesting discussion of the differences in the illustrations of the 1669 and 1758 editions see Geoffroy Fryer, 2008). In Fryer's (2008) discussion, he focuses on the comparative method employed by Schäffer to explain *Daphnia* feeding mechanisms. Fryer includes a short paragraph (Fryer 2008: 170-71) describing Swammerdam's contribution to Schäffer's research on *Daphnia* feeding that explains that these stylized illustrations were in part due to later illustrators attempts to capture more what they thought were a more accurate depiction of Swammerdam's (incorrect) description that water fleas had beak-like structures and that their feeding mechanism was akin to an insect's proboscis. The result is that the original 1669 illustrations, drawn from life by Swammerdam, are a truer representation of the water flea Daphnia than the later *corrected* version in 1758.

Fig. 1 The title page of Swammerdam's 1669 *Historia Insectorum Generalis.* Reproduced with kind permission from the Linda Hall Library of Science, Technology, and Engineering

Fig. 2 Swammerdam's 1669 illustrations of his newly dubbed organism, "pulex acquaticus arborescens", (labelled from right to left B, A, and C) from his Tab. 1. The smallest illustration labelled "A" (in the middle) is noted by Swammerdam to be "actual size". From Swammerdam's 1669 *Historia Insectorum Generalis.* Reproduced with permission from the Linda Hall Library of Science, Technology, and Engineering

Fig. 3 Close-up image of Swammerdam's (1669) original illustration, "C". From Swammerdam's 1669 *Historia Insectorum Generalis.* Reproduced with permission from the Linda Hall Library of Science, Technology, and Engineering

Swammerdam complemented his detailed illustrations with extensive and detailed descriptions of the fleas' morphological and behavioural characteristics with liberal use of analogy and references to comparative structures of known organisms and machines. He writes,

> "I shew an eye in one side of the head, fig II, A. and under it a sharp beak C. On the breast are seen arms, divided into branches like the boughs of trees… [the flea] is transparent [and] the colour of this insect inclines somewhat to red in the full grown; and is like that of beef, which has been some time steeped in water. The outward structure of the skin that covers it agrees, in some measure, with the rhomboidal and checquered shell skin of the scaly fish; though I could hitherto see no scales in it (Swammerdam 1758)."

Because of the tree-like structure of their second antennae he dubs his subjects "pulex aquaticus arborescens" (Swammerdam 1669) and "*Arborescent* Fleas" (Swammerdam 1758). Swammerdam attempts to familiarize his readers with not only the gross morphology but also the structure of the new and as yet undescribed organism he observes. By using analogies and metaphors of those things commonly known by his readers—the branching structure of trees and vertebrate anatomy, he is able to make known to his readers the structure of the organism he observes. The organisms' tree-likeness significantly shapes the language he uses to describe their structure:

> "They [the second antennae] arise undivided from two, as it were, simple trunks, which, like the shoulder bones, spring from the shoulder blades, and are each divided into two branches; each of these is again subdivided into three different joints. At the first and second joint, reckoning from the single trunk, there arise on each side a little branch, almost like a hair; and at the third or extreme point, three such buds or shootings are placed, which also seem to be again divided into other joints" (Swammerdam 1758)

Swammerdam observed live specimens, describing their motion as like the distinctive jumping of fleas. Continuing to use analogical descriptions of organisms and mechanisms commonly known, he describes the movement as follows:

> "first, the little creature can, with their assistance, move in a straight line; whilst it constantly waves its ramified arms, as a bird its wings in the air,…a second motion is like that of the sparrow, for as these, by expanding and again contracting their wings, pass with an uneven motion throught the air, and sometimes descend and immediately after are carried aloft again…it happens that it is continually seen to jump in the water,…like the whirling or turning about of that kind of pidgeons…or may be compared to the turning of a wheel about the axle-tree of a chariot" (Swammerdam 1758).

The use of analogies in his descriptions of both movement and morphology of the water flea furnished Swammerdam with exceptional explanatory power. Firstly, they enabled him to make sense of the organizational structure and locomotion of the strange organisms in front of him, and second, they furnished him with ways to communicate his understanding of structure and movement through pictographic and descriptive language that conveyed meaningful explanations about his observations to an audience unfamiliar with his subject.

Despite his vivid descriptions and careful illustrations, there was little interest in the water flea after Swammerdam's initial studies. There was no mention of them in Linnaeus' 1735 *Systema Naturae* (Ashworth 2009). It was not until Jacob Christian Schäffer's monograph *Die Grünen Armpolypen* (1755/1763) that another detailed study of the water flea was published. In describing and naming the water flea, Schäffer did not use Linnaean binomial nomenclature, instead Schäffer named it "*die geschwänzten zackigen Wasserflöh*" (the tailed, branched water flea) (Ashworth 2009). At the time, what would be roughly equivalent to genera, kind, family, or other supra-species names were frequently suggested in preference for more specific classifications. Schäffer among others simply referred to these as general "kinds" (Fryer 2008).

Using an early compound microscope[11], Schäffer's detailed descriptions and illustrations of water flea microanatomy, function of the parts, locomotion, and behaviours extended and improved upon Swammerdam's original studies. Illustrations in Schäffer's *Die Grünen Armpolypen*[12] were much more numerous, in colour, and included a high level of detail of many of the more nuanced characteristics of the water flea. He also depicts a different kind of water flea which he names "*ungeschwänzten zackigen Wasserflöh"* due to the lack of tail spine (this is most likely a water flea of the family Daphniidae, *Simocephalus vetulus*) (Fryer 2008; Ashworth 2009).

[11] Schäffer most likely used a Culpeper type microscope (Fryer 2008).

[12] Schäffer's illustrations were drawn by a professional artist which was common practice at the time (Fryer 2008). Curiously, after Swammerdam's *Historia Insectorum Generalis* and Schäffer's *Die Grünen Armpolypen*, many naturalists did not continue to use microscopic investigations as the basis of their illustrations but instead simply used Swammerdam's and Schäffer's illustrations as reference guides, often re-drawing Swammerdam's original illustrations (Fryer 2008).

Fig. 4 Tab.1 from Schäffer's *Die Grünen Armpolypen*, 1755. Reproduced with permission from the Linda Hall Library of Science, Technology, and Engineering

Fig 5-7 Close-up images of Schäffer's *Fig. IV, VI, VIII* from Tab.1. The image labelled *IV* is Schäffer's *"geschwänzten zackigen Wasserflöh"*, likely to be a *D. pulex*. The image labeled *VIII* is Schäffer's "*ungeschwänzten zackigen Wasserflöh"* which is likely to be a *Simocephalus vetulus.* From Schäffer's *Die Grünen Armpolypen*, reproduced with permission from the Linda Hall Library of Science, Technology, and Engineering

It is perhaps in some ways unsurprising that knowledge of these pre-Linnaean techniques of observation, description, depiction, and classification of the water flea have neither been retained nor widely discussed within many of the specialist sciences that now rely on *Daphnia* as model organisms in their research. *Daphnia*'s use as a research model in environmental, limnological, biomedical and toxicological studies does not require historical knowledge of the origins of observational and descriptive techniques. In these fields this knowledge is not necessary to the development of new knowledge and applications. In fact, in order to get on with the research within these fields, certain bits of historical knowledge must be excised from the corpus of currently accepted scientific knowledge and practice. These are not used or retained within the science. However, this loss of knowledge presents an opportunity for historians and philosophers of science and students to take on the role of complementary scientist (following Chang 2011) to investigate and critically re-examine the work of the early naturalists' depictions and descriptions of the water flea and their repeated attempts to resolve various species complexes.

5 Research, collection, and lab investigations

I structured the HPLS project into 5 stages: 1) historical research and study; 2) collection of specimens; 3) the use of recovered techniques and nomenclature of early naturalists; 4) the use of updated techniques and nomenclature, and lastly, 5) reflection and analysis. Students began by studying the descriptive writings and illustrations contained in the original texts of Swammerdam and Schäffer. Studying the early naturalists' writings and illustrations of their own specimens collected from ponds and lakes in their local vicinity[13], I was interested in staying as true to the kinds of collection techniques and procedures of these early naturalists as possible. Since they collected samples of water fleas from their own local environments, I thought we should also rely on our own local microfauna. Instead of ordering stocks of *D. pulex* or *D. magna* from a scientific supply company I thought it would be fun for the students to collect samples of the water fleas that were present in two of our university campus ponds.[14]

In the lab, I worked alongside the students. To begin, we isolated three individuals from each sample that were chosen at random giving us a total of 12 specimens. Each flea was named and labeled with its collection data. In our initial stage of observations we utilized the discarded historical techniques of the early naturalists' microscopic observations, analogical descriptions,

[13] Swammerdam performed many of his studies in Leiden and Amsterdam, Netherlands (Ruestow 1996). Schäffer mainly performed his studies in what is now Regensburg (originally Ratisbon) Germany (Fryer 2008).

[14] A month before I brought the students to the ponds to collect specimens, I went with a colleague in the biology department to collect samples to make sure that there were indeed *Daphnia* present in these ponds. Later, I went with the students to collect samples for the project. We used plankton nets to collect samples. For each pond we collected one sample from the top and one from the bottom.

detailed illustrations, and nomenclature that we recovered from our research of Swammerdam and Schäffer. The aim was not to attempt to replicate their historical investigations but to best approximate their use of techniques and methods of description whenever possible. Despite research into their use and operation, we had no access to Culpepper microscopes. We instead used low magnification dissecting microscopes set from 7x to 35x for our own observations and drawings of the water fleas from life.

I provided students with lab protocols but also encouraged them to think independently about their observations and how to record these using the recovered techniques and descriptive methods from Swammerdam and Schäffer. Once they grasped that there were no prescribed results and that the investigation was not staged, they were excited by the prospect of working as fellow researchers working out the results of what many called a "real experiment". Working in the lab within the context of an HPLS course and observing *Daphnia* for the first time, students were invited to interact with their research tools and their yet-to-be-discovered organism as if they were working outside of normal science.[15] This was especially liberating for some science students who had developed a particular disdain for the notion that the majority of scientific activity is composed of puzzle-solving that takes place within an unchallenged paradigm during periods of what Thomas Kuhn called "normal science" (Kuhn 1970).

Students were invited to apply the recovered classification schemas, techniques, and methods we found to the study of the samples of our locally collected microplankton. The students and I illustrated[16] and described each organism with an eye to identifying it as either being the same species or a different species than those identified in Swammerdam's and Schäffer's monographs.

[15] Students were using equipment properly and abiding by the rules of acceptable and appropriate lab behaviour so strictly speaking were still working within the paradigm of normal science, but insofar as they were invited to think beyond the "cook-book" type experiments and observations sometimes performed as pedagogical exercises in science labs, they were striving to act *as-if* they were outside normal science. Although these "cook-book" type experiments are extremely effective in allowing students to grasp key concepts in science courses, this type of investigation was not my aim. Instead, it was to allow them to do much more exploratory work. I admit that the use of the Kuhnian language here may be overreaching but it was useful in explaining to the students what I wanted them to consider when coming into the lab and what they were at liberty to do once they were in the lab that they were not permitted to do in the context of their other labs.
[16] We produced a total of 15 illustrations.

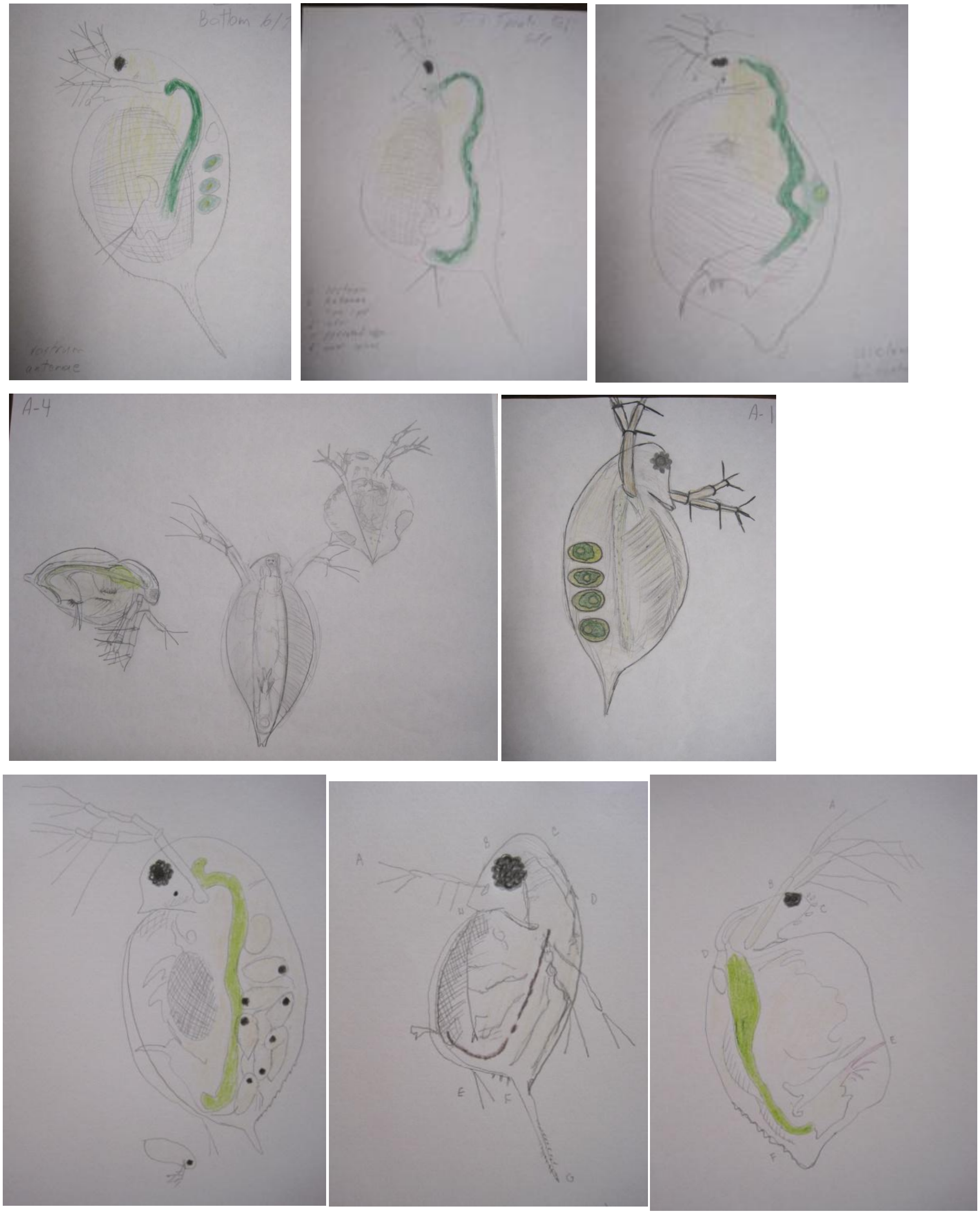


Fig. 8-15 This is a selection of the 15 illustrations of the 12 specimens drawn by us in the first stage of the project. These illustrations are drawn from life using low magnification dissecting microscopic observations

The following is a representative sample of the students' descriptions:

> *"The arm of J3 is very thick and powerful with a claw that is only partially hooked. The claw is shaped like a cat's claw, curved but not a severe hook… Both the back and front edges of J-3's carapace are serrated including the tail spine, which is long and narrow. The serrations are similar to the serrations you would see on a hand saw*" (Swindler notebook 1, 2011).

> *"Viewing the specimen (A4) from the ventral side it appeared as if there were many internal structures running the length of the organism that were pulsating in a rhythmic fashion. It was seen that the foot would occasionally kick. It also appeared as if the organism was incased in a structure that appeared shell like… The head of the organism did not appear like a bird but more elongated and flat near the bottom. The head and the eye structure appeared like a miners helmet with a light affixed to the front of it. The dorsal section of the body did not run smooth from the rostral to the caudal end but instead was indented in on itself near the back of the head*" (Anderson notebook 2, 2011).

After completing their illustrations and descriptions, I asked the students to compare the morphological features and behaviours we observed and recorded in our samples with those depicted and described by Swammerdam and Schäffer. For each sample, the following questions were answered: Is this the same kind of organism that is described by Swammerdam or Schäffer? How is this judgment being made? What characteristics and behaviours are used in making this decision? What is my level of confidence that these are the same (or different) kinds of organisms?

Relying on the historic texts, our own low microscopic investigations illustrations, descriptions, and considering our answers to the above questions, each organism was then identified as either similar or dissimilar to those individuals described and illustrated by Swammerdam and Schäffer.

After completing these initial observations utilizing recovered techniques in the first stage of the project, we then augmented these with up-to-date classificatory theories, methodology, techniques, and equipment. In the second stage of the project, we monitored the water fleas for morphology and behaviour using a stereomicroscope (Leica M165 FC). We captured pictures using a QI imaging camera and Q capture Pro 6.0 imaging software.

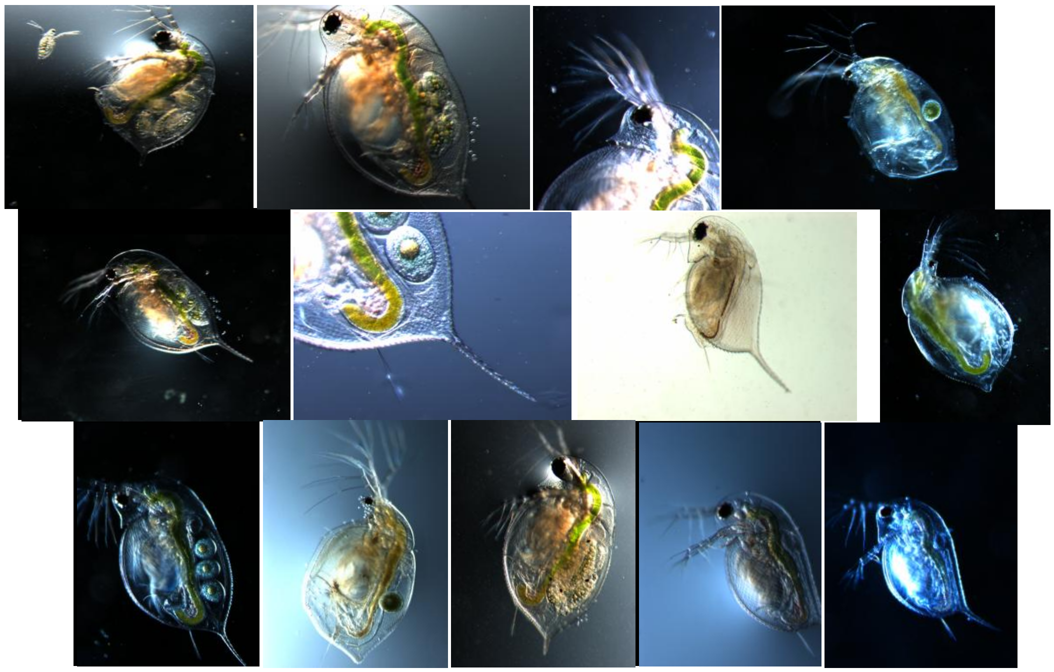


Fig. 16 This is a small selection of the 60 photographs of the 12 specimens we took in the second stage of the project using a stereomicroscope (Leica M165 FC), QI imaging camera, and Q capture Pro 6.0 imaging software

Our investigations produced a set of data that included 15 drawings, 60 photographs, and detailed descriptions based on our observations of 12 specimens from diverse ecologies (from the top and bottom of the two different university ponds). Using these data and combining the methods of both the recovered techniques and a simple up-to-date technique[17] used in quick

[17]Current identification of waterfleas entails more than simply using photographic keys. The choice to use a image key for the present project was in part due to its ease of use for students unfamiliar with more complex taxonomic techniques. To be sure, their use in the project was not intended to indicate a replication of the process of classification currently in use but instead was used as a quick examination that aids in research in the initial stages prior to more detailed analyses. The use of the image-based key rather than the use of keybooks traditionally used by specialists to distinguish species using diagnostic characters (see for instance Benzie 2005) provided a structure to the project that allowed adequate time to each of the central stages of HPLS research necessary for the project—a close reading of the primary source materials and arguments, philosophical analyses of these, and the requisite historical research that was prerequisite to the study based on Swammerdam and Schäffer's observations, the lab observations and drawings inspired by Swammerdam's techniques, and an evaluation using recent techniques of classification. Combining the use of DNA sequencing, modern taxonomic drawings, scanning electron microscopy, as well as photographic evidence would have been a desirable extended project that would have contributed to a more accurate representation of the specialists' techniques of the classificatory process. However doing so would

examinations of waterfleas, we identified the genus and species of each of our 12 specimens using a current image-based key to zooplankton.[18,19] In the final stage of the project, I asked students to write essays focussing on an aspect of the project that was of particular interest to them reflecting on their role as complementary scientists and their HPLS course readings. [20]

6 How can HPLS observations and investigations augment science education?

The purpose of the description of this project is two-fold: it explores the possible pedagogical benefits of implementing Chang's suggestion for HPLS and science education, and it suggests another area of study where historical experiments have seldom been used, the biological sciences. Significant differences exist between historical experiments in the physical sciences and historical observations, depictions, and descriptions that are the keys to investigation in biological classification. The pedagogical use of historical experiments or investigations in the physical sciences is well documented (e.g. Gooding 1985, Sibum 1995, Cavicchi 2006). But their use in the biological sciences is rare (Chang 2011: 319). Considering some of the difficulties encountered in the project being discussed herein, there may be a number of possible reasons for this.

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have required a much more lengthy project and one that would not have been possible within the confines of the present course but could be appropriate for an advanced philosophy of biology course or an interdisciplinary project within an advanced systematics course. Integrating these varied tools of observation and analysis within such an extended project one could rely on recent studies such as those which use illustrations for understanding functional morphology such as Fryer (1991) and Kotov & Taylor (2010).

[18]The key we used was the UNH Center for Freshwater Biology's Image-based key to the zooplankton.

[19]We found that we had 3 *Daphnia rosea*, 3 *Simocephalus serrulatus*, 1 *Daphnia schødleri*, 2 *Daphnia catawba*, 1 *Daphnia ambigua*, 1 *Simocephalus vetulus*, and 1 unknown. Rather than trying to replicate the methodology of current *Daphnia* specialists, students were advised to use the image-based key as a rough field guide resource for initial investigation.

[20] An extension of the present project could focus on plasticity, ecotoxicology, and homology studies by working in tandem with an ecologist and biochemist. Such a project could explore ways of manipulating the environment of the *Daphnia* using chemicals that are structurally similar to kairomones. Because this would require a more substantial amount of time, it is in the process of being planned as part of a summer research project. Students will record changes in the morphology and behaviour of the *Daphnia* and use these to interrogate past classifications based on a variety of different polyphenisms. These investigations would focus on the neckteeth and other defensive mechanisms of *D. pulex* developed in response to the presence of predatory planktivorous Dipteran insect larvae of the genus Chaoborus (which were also found to be present in the university ponds). This project will use combined methods of investigation in ecology and biochemistry. The hope will be to isolate the ecological polyphenisms and induced defensive morphologies of various species of *Daphnia* and go on to compare them to find possible phenotypic and genetic homologues (in *D. magna*).

Replicating historical investigations that recover past observational knowledge in the biological sciences takes a different shape to the kinds of experiments performed in physics and chemistry. The biological sciences focus as much on what Ernst Mayr (1997) calls "what?" questions as "how?" and "why?" questions. "What?" questions are not just questions about descriptions and the enumeration of a biological collection akin to "stamp-collecting" [21], they are questions which are directed to the understanding of "the kinds and diversity of organisms, ...any and all relationships among them…[and] the comparative study of all characteristics of species" (Mayr 1997:125).

Although these processes are of course not unique to the biological sciences, observation plays a particularly large role in the processes and techniques required for classification. Knowing what kind some living being is greatly informs what other information we can infer about it, e.g. knowing what kind something is means we know what inferences we can make about it and what generalizations apply to it as a member of that kind. Understanding if it is of one kind rather than another requires close and careful comparative observations of behaviour and morphology.[22]

The goal was to come up with a proposal for a project that could be planned, organized, integrated, and executed within the scope of a cross-listed HPLS course. A series of labs that were appropriate and accessible but also intellectually challenging was sought to provide students an opportunity to explore the role of philosopher of science as complementary scientist. The intention for inclusion of this element of the course was to allow students to explore in the lab the questions that were raised throughout the course readings. The series of labs would provide a space for them to bring the *practice* of investigation, observation, and classification to bear on scientific explanation. And this would allow students to explore how explanations explain, how descriptions are explanatory, and what makes explanations knowledge producing, and consider the possible order (or disorder) in the natural world and how we can understand it in practice.

[21] This phrase comes from the famous quote attributed to Ernest Rutherford, that "all science is either physics or stamp-collecting."

[22] One of the topics covered within the HPLS course is natural kinds and their relationship to biological taxa. The lab, in some ways, is an attempt to bridge the philosophical discussion of natural kinds and the practice of classification using various notions of biologically construed kinds. It does so by focusing on the notion of kind-hood and how this has changed and been shaped by observation, description, and tools of investigation and recording.

Throughout the HPLS course, students studied the key articles discussing scientific knowledge and explanation. Scientific knowledge is not about detailed descriptions of each and every observation but instead is often achieved by generalization, or as Philip Kitcher (1981) suggests, by unification. While others (e.g. Dupré 1993, Hacking 1996) suggest the underlying assumption behind the hypothesis *that explanation is unification* is faulty, and that there is no reason why the assumption of unity should be privileged over that of disunity in the natural world. Further questions arise such as: how do we know what unifies?, and why is explanation by unification explanatory? It seems obvious that the sciences do not simply produce a pile of unrelated bits of knowledge, but it is much less obvious as to *how* the sciences provide us with explanation and how this yields understanding about the processes, causes, and kinds of things which make up the natural world. After exposing students to these epistemological and ontological debates within the history and philosophy of science, I wanted them to consider these questions *in situ.*

The pedagogical benefits of integrating Changian complementary experiments or investigations like the one described herein can enhance science education within an HPLS class in four ways: 1) they provide a venue to study key figures and techniques in the history of biology not addressed in biology textbooks, 2) they provide divergent lab activities that invite students to explore interdisciplinary problems, 3) they allow students to question accepted methods and techniques in their area of research in an appropriate setting, and finally, 4) they provide an opportunity to augment scientific knowledge.

Normal science education often relies on the knowledge and understanding students can gain from repeating the experiments described in biology textbooks in biology labs as exemplifying key features of the corpus of accepted scientific knowledge (Devons and Hartmann 1970; see also Kuhn 1970). The replication of these kinds of experiments, the interpretation of photographs in textbooks and pre-prepared slides are both useful and informative for learners in these fields. But complementary experiments and investigations such as those described here and throughout Chang's work can enhance students' learning in divergent but harmonizing ways to those traditionally used in science education.

Investigating forgotten historical techniques of observation and lost classificatory descriptions and names like those of Swammerdam and Schäffer highlights the problems associated with classification that are absent from many university biology textbooks, (see, for example, Ricklefs & Miller 1999 and Campbell & Reece 2005). The recovery of these historical observations by students themselves introduces them to these conceptual and operational difficulties in a very direct and immediate way.

This project also led to a modest discovery and suggestion for future use of *Daphnia* as pedagogical research tools.[23] As a result of our active use of the recovered methods and discarded techniques of the early naturalists, we found that these may provide additional knowledge relevant to the study of *Daphnia* morphology that may help to resolve their classification. In the process of creating illustrated representations from our observations of the live specimens (following the practices of Swammerdam in particular), we found that this process significantly contributed to our understanding of the morphology of our subjects. Upon reflection, we realized this was due at least in part to the concentrated attention that was required to produce accurate illustrations. For each illustration, it was necessary to observe the live specimen under low magnification for an average of 90 minutes.

We found that these techniques increased our ability to make the fine-grained discriminations necessary for morphological classification. But what may be surprising is that we found that the process of drawing these live specimens was useful not just in our investigations using recovered techniques and descriptions based on the work of Swammerdam and Schäffer. We also found that drawing from life improved our ability to identify certain behaviours and characteristics that helped us better identify certain key morphological features necessary in our updated observations using the stereomicroscope and the updated classification techniques utilizing the image-based classification key to zooplankton.

Knowledge gained through the close study required to produce faithful representations of the specimens in our illustrations informed our decisions as to which features we focused on when using the stereomicroscope and capturing images. In the process of drawing the water fleas we became aware of the differences in body shape, size, length of tail spine, neck curvature, number of bristles on the anal spine, and other minute details used for morphological classification. This attention meant that we were then better able to identify the characteristics that changed from individual to individual. Making illustrations of the live *Daphnia* from our observations seemed to force directed attention to details of their microanatomy. I suggest that

[23] The suggestion here is that the use of these historically informed observations and drawings could be effectively integrated into both biology labs as well as HPLS labs. While the project was completed within a state university in the U.S., it could be replicated in any institution.

this, combined with the use of multiple disciplinary approaches in the course of the project yielded unique scientific understanding.[24]

In this way the recovered knowledge of some of the techniques of observation and classification informed and directed our use of the updated observational techniques in capturing images of the water fleas using the stereomicroscope and imagining software in the second stage of the project. Reflecting on our use of both recovered and updated techniques, we concluded that while high magnification photos provide much more detail, and often more accurate representation of an organism than a free-hand drawing, the *process* of drawing out the individuals observed reveals a lot about their morphology that goes otherwise unnoticed. Much of the knowledge gained in attempting to produce accurate representations came from the close attention to the function and movement of certain structures.[25] Although sometimes quite difficult to draw and photograph, observing the movement and functioning of live specimens provided more information about the specimen's morphology and structure than would have been obtained from observing dead ones. Information about how the various parts of the organism fit together allowed for a more accurate rendering of the specimens under investigation by revealing the modularity of the parts of the organism as well as the integration and organization of these parts within the whole organism.[26]

One impact our project may have in improving scientific understanding of zooplankton classification and research in multidisciplinary research projects is that current protocols in

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[24] This requires some qualification. Whilst detailed drawings may be retained within the toolkit used by some specialists studying *Daphnia,* the use of these plays a much more minor role in current research than they did in Swammerdam's or Schäffer's. The claim here is that the *epistemological use* of drawings, and more pointedly the process of drawing and observation that was key to Swammerdam's initial investigations, was a knowledge-producing technique that was lost. Other knowledge producing techniques (i.e. the use of scanning electron microscopy, genetic and molecular data analysis) now often trump, if not replace, these in distinguishing one species from another.

[25] This was shown to be of significant pedagogical value within a history and philosophy of the life sciences course. This value was not affected by the skillfulness or illustrative talent of the students or by their skills in photographing the *Daphnia*. Students engaging in illustrating and then photographing the *Daphnia* all benefitted from performing these techniques within the context of the historical study and in the later evaluative stages. Evaluative reports following the completion of this project showed that the entire cohort found that the study of Swammerdam and the replicating the low magnification observations and illustrations provided an understanding of the structure of the organism that was useful in later investigations using the stereomicroscope and imaging software to capture images of the anatomical structures relevant to classification. This may not be generalizable to other potential cohorts but it was reported universally within the present one.

[26] During the project we found that once daphnids die they change colour and their muscles begin to disintegrate. This change and disintegration compromises one's ability to make fine discriminations between similar specimens. This could be used to suggest that if dead daphnids are routinely used and photographed for the purposes of representing a particular species in image-based morphological classification keys that these might not be the best representations of *Daphnia* and may perhaps affect classifications based on these.

Daphnia research may be questioned. Some current protocols in *Daphnia* research suggest that microscopic investigations are recorded with photos but not illustrations. Protocols for *Daphnia* sample collection and analysis also widely suggest the use of preserved dead specimens (see Barker, Mays, and Cangelosi 2011[27]; and Standard Operating Procedure for Zooplankton Sample Collection and Preservation 2005[28]). Through our investigations as *complementary scientists* using discarded techniques and descriptions from the early naturalists, we found that some of these greatly improved understanding and knowledge. From the discarded techniques we recovered there may be some practices and processes of representation that may be valuably reclaimed and may be a useful addition to the current toolbox of techniques used in HPLS integrated labs on zooplankton classification and integral to a robustly interdisciplinary science education.

Complementary investigations in HPLS provide an opportunity for students and their professors to explore basic questions about the nature of scientific knowledge—what is it? and by what means can we obtain it? Introducing science majors to the key papers on demarcationism, theory choice, scientific progress, and incommensurability from Popper, Kuhn, Lakatos, and Feyerabend often leaves them feeling unsettled. Questions like: what is science? and how can we distinguish it from pseudoscience? can strike different students as initially quite silly with obvious answers; exceptionally challenging; and at times threatening. These strong reactions can be an opportunity in the context of a course in HPLS where (to some extent) the rules of proper lab protocols do not apply. The use of complementary lab investigations such as those discussed herein based on the re-examined techniques used by the early microscopists that led to Swammerdam's discovery, description, and depiction of the water fleas in 1669 enhances interdisciplinary research experience for undergraduates and contributes to integrated learning by emphasizing the idea of science as practice (an idea which can sometimes be lost when focussing purely on the close reading of key texts). Complementary experiments offer an opportunity for students to think about historical scientific writing as the product of activities practiced in the lab

[27]The Great Ships Initiative, Standard Operating Procedure for Zooplankton Sample Analysis suggests killing the zooplankton prior to classification by "add[ing] 1 or 2 drops of 50% acetic acid solution to the slide. Let the slide sit for a few minutes in order to kill all organisms, then count the total number of organisms…" and later "add a few drops of diluted Lugol's (5% solution) to the chamber to kill the organisms…" (p. 5).

[28]The Standard Operating Procedure for Zooplankton Sample Collection and Preservation suggests organisms are "narcotized with soda water and preserved with sucrose formalin solution" (i.e. killed and sugar-coated, see Haney, J.F. and D.J. Hall 1973. Sugar-coated Daphnia: A preservation technique for Cladocera. *Limnology and Oceanography* 18: 331-333).

or in the field with a different set of tools, methods, and background knowledge. It provides a space for safe but innovative thinking that can complement their learning by linking the product of science (knowledge) with the processes and activities necessary to achieve it.

Classic experiments and observation techniques used to instruct and inform students of the importance and purpose of biological classification often make assumptions about the methods and techniques that must be used. This project attempted to examine these parts of the process of scientific knowledge acquisition thought to be beyond criticism—those methods and techniques of observation (e.g. such as those stated in lab protocols) through the use of alternative methods of observation and recording recovered from the early naturalists.

Historical experiments and investigations need not be restricted to disciplines in the physical sciences where discussion of these has been more common. As the preceding discussion of the present HPLS project suggests, the role of philosopher of science as complementary scientist is a role that brings with it many pedagogical opportunities for student learning in the biological sciences and the history and philosophy thereof. It is hoped that this description of one possible HPLS project will provide impetus for further complementary historical investigations.

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