Understanding complex systems: lessons from Auzoux's and von Hagens's anatomical models†

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Animal and human anatomy is among the most complex systems known, and suitable teaching methods have been of great importance in the progress of knowledge. Examining the human body is part of the process by which medical students come to understand living forms. However, the need to preserve cadavers has led to the development of various techniques to manufacture models for teaching purposes. A variety of materials, such as wax, wood, *papier-mâché*, or glass, have long been used to construct animal and plant models. In the case of the human body, the most innovative, yet controversial, method of preservation has been plastination, invented by the German physician Gunther von Hagens, by which actual human bodies are preserved as odourless and aesthetic models for teaching and exhibitions. We point out in our study that the 'hands-on' approach that some anatomical models allow, namely, the (clastic) disassembly and reassembly of the parts of complex systems and their models, is not only a crucial tool for learning, but is far superior to the simple passive observation that rigid, single-piece models allow. And what is valid for the learning of anatomy can be generalized to the acquisition of knowledge of other complex physical systems.

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1. Introduction

Common to science and art is the potential to be creative. In science, creation flows from proposing new questions and hypotheses and from providing new empirical data in the endless interrogation of Nature. New views supersede present knowledge on the ground that what is surpassed has been sufficiently understood, or they run the risk of rediscovering prior ideas. Art provides alternative, constantly changing ways of seeing and representing Nature.

Suitable teaching methods of what is already known are the condition *sine qua non* for the discovery of new factual knowledge and for the creation of new ideas, which are often a reformulation, reinterpretation, or reintegration of previous knowledge. This transmission of knowledge and experience ought to take place in theory and practice or, in other words, in interpretation and interaction. Teaching without practical examples is as useless as experimentation without hypotheses or questions. In short, teaching with practice is the way to provide students with sufficient experience and expertise and is 'a necessary component' of science (Howie 2002).

Human and animal bodies are among the most complex objects to study and understand. Early empirical knowledge, accumulated through observation of and intervention on animals and injured and intact human bodies, and skeletons by Hippocrates, Aristotle, Herophilus and others, was synthesized in the works of Galen and subsequently transmitted and studied by the following generations through word and repetition, without re-examination. This almost annihilated the normal procedure that gives rise to new knowledge, leading to a stagnation of the collection of new empirical data (Malomo *et al.* 2006). The same cannot be said of other cultural traditions, though, as the contributions by physicians in the rising Islamic and other

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†Dedicated to the generation of students who have grown up with virtual computer worlds. May they find delight in the manipulation of earthly objects.

parts of the world attest (Hehmeyer and Khan 2007; Shoja and Tubbs 2007).

During the High Renaissance, a new period of advancement in anatomical science started under the influence of Andrea Vesalius (1514–1564), who was the driving force for a return to the direct observation of human anatomy, without which further advancements in medicine would not have been possible (Porter 1997).

The practice of direct observation was severely limited, however, due to the difficulty of preserving cadavers at least for the duration of a dissection. This limitation dominated human anatomy well into the middle of the nineteenth century and has been a convoluted and controversial subject in medicine and literature. To give just one example, in 1746, the Scottish physician William Hunter announced his anatomical lectures 'during the whole winter season in the same manner as at Paris', meaning that students were offered the opportunity to dissect real human cadavers (Gelfand 1972). As is noted in this announcement, lectures were usually held during the winter, when cold storage of cadavers was possible and, hence, fresh or at least less decayed bodies were available for dissection (Richardson 2000).

A comparable problem was encountered in the preservation of organisms other than humans by the cabinets of natural history, the predecessors of modern museums, such as those of Francesco Calzolari (1521–1600) or Ferrante Imperato (1550–1625), which held mainly dried specimens, skins and hard parts less prone to decay (Findlen 1994). Until 1666, the only way to adequately preserve dead organic material was in a dry state. Robert Boyle's experiments with the 'spirit of wine' made it possible to prepare wet specimens that could endure the passage of time and offer a fresh and natural look (Asma 2001). Formaldehyde as a fixative became available in 1893 (Porter 1997). Therefore, a crucial resource for expeditions in search of new organisms overseas were the 'Instructions for collectors', such as the very successful '*Instructions for collecting and preserving various subjects of natural history'* (1794) by Edward Donovan, which saw a translation (supplemented with additional information) to German by Romer (1797) before it was reprinted in 1805. In it, various techniques for the preservation of biological specimens were detailed and frequently suggestions on data acquisition beyond the 'physical remains' were included (Larsen 1996).

The challenge of obtaining biological material in a condition that allows manipulation, and with a texture and consistency that is conducive to learning, has been addressed by numerous medical practitioners (Saeed *et al.* 2001; Roda-Murillo *et al.* 2006). Various methods have been used throughout the history of medicine to circumvent the problems relating to human cadavers for teaching human anatomy, but the manufacture of models has been one of the most successful solutions, at least as introductory materials. Models of the human body and its parts, as well as of other organisms, have been made of wood, wax, glass and even preserved bodies (table 1). Some of the best-known model types are the wax models of the Italian school (e.g. Poggesi [1999], and references therein), which have received attention for their usefulness as pedagogic tools as well as for their aesthetic value. Less well known are the models developed by the French physician Louis Auzoux (1797–1880), which combined great realistic features with the possibility of moving some parts. More recently, the German anatomist Gunther von Hagens (born 1945) has developed a new technique called plastination, which has had enormous success as pedagogic material and artistic representation. The fact that Auzoux's and von Hagens's models are credited with artistic qualities makes both men deserving of special attention in the history of the practice and teaching

Table 1. Characteristics of five different types of anatomical models

Properties of models	Wax	Papier-maché	Plastination	Wood	Glass[5]
Movability	No[1]	Yes[2]	No	Yes[3]	No
Number of cadavers needed to produce one model	200[4]	No information	1 to 1	200	Unknown
Degree of needed expertise	Easy	Easy	Time-consuming	Difficult	Easy
Durability or fragility	Fragile	Durable	Durable	Durable	Fragile
Human models	Yes	Yes	Yes	Yes	No
Animal and plant models	Yes	Yes	Yes	Unknown	Yes
Price	Expensive	Relatively inexpensive	Expensive	Expensive	Relatively inexpensive

(1) A few historical specimens had mobile parts.
(2) The term 'anatomie clastique' derives from the Greek word *klastos*, broken into parts.
(3) Tendency to warp with time (Poggesi 1999).
(4) Poggesi (1999).
(5) *See* Sigwart (2008).

of human anatomy. At the same time, their work allows a consideration of the values and limits of physical models for the process of human learning. Our essay takes these two authors as relevant examples to elaborate this point.

2. Auzoux and von Hagens: different methods with the same objective

Louis Thomas Jerôme Auzoux (1797–1880) was born in Saint-Aubin-D'Ecrosville (France). During his time as a student of medicine, he was confronted with the lack of corpses for the learning of anatomy. Drawing from the experience with dolls made of *papier-mâché* – a mixture of paper and gum – Auzoux conceived and built accurate replicas of organs and whole organisms, including human bodies with a refined *papier-mâché* technique that included naturalistic paint and with additional functionality that became the 'mark of the house': the human and animal models were made of parts that could be disassembled allowing a 'hands-on' experience with the anatomical models. Auzoux called this new technique 'clastic' (i.e. movable) from the Greek *klastos*. Previous models made of wax or wood were usually rigid pieces, offering only a single aspect of the original material. Only occasionally were singular pieces produced with a few movable parts.

The first complete clastic human model was presented by Auzoux in 1822, and five years later, he opened a factory in his native village for the production of animal and human anatomical materials for medical, biological and veterinary schools. The models were very successful because of their great educational potential, and the factory kept producing models well into the twentieth century (Grob 2004).

Gunther von Hagens (born 1945) studied medicine at the University of Heidelberg at whose Institute of Anatomy and Cellular Biology he became a scientific collaborator. In 1977, he invented a new method to preserve organs and bodies by substituting body fat and fluids with reactive polymers, such as silicone rubber, epoxy resins and polyester. The technique received the name of plastination and resulted in odourless objects that withstood the wear and tear of handling. After plastination, the plastinated specimens, which do not retain the original size and colour, need to be treated further to recover their original colour and size. The Institute for Plastination was founded by von Hagens in Heidelberg in 1993. Since then, plastination has changed the way the human body can be represented, and its application to other biological materials has gained followers in schools of medicine and biology all over the world. Von Hagens has produced the first exhibition of plastinated human bodies and organs, which he called 'Body Worlds' (a new exhibition 'Body Worlds and the Cycle of Life' opened in 2009 in Berlin). Von Hagens considers that plastination is more than a simple technique to preserve organic materials; he believes that it is a combination of technique and art, in the special sense that he calls 'anatomy art', in which the aesthetics of perception is combined with a pedagogic purpose (von Hagens 2002).

3. Science, representation and learning

At some point in time, previously familiar objects may become subjects of amazement or admiration. This may occur, in part, for three reasons: (1) age; (2) uniqueness; or (3) beauty. Archaeological objects collected by museums have different values according to these three criteria. Roman coins, commonly found at some sites, are valued under the criterion of age, but do not receive special attention with respect to uniqueness or aesthetics. There are other objects that are considered valuable by all three criteria as is the case with the marble statue of the Winged victory of Samothrace (ca. 220–190 BC).

The use of these three criteria may be questioned when valuing objects in modern museums and trying to predict their future value. In the case of Auzoux and von Hagens, it would be appropriate to include the pedagogical value of their models as an additional fourth criterion. Their models have crossed the boundaries between the teaching laboratories in medical schools and displays in public exhibitions. Today, Auzoux's models maintain their pedagogical value, even though their growing scarcity has rendered them collectors' items.

Models used in science and education could be analysed from different points of view, such as from a purely objective point of view, as Daston and Galison (1992, 2007) have done with drawings and photographs, or from a historical or philosophical point of view (Chadarevian and Hopwood 2004). In contrast, our own evaluation of models focuses on the characteristics that make them appropriate for learning and transmitting knowledge, an activity that can never be considered completed and that heavily depends not only on the richness of detail of the models, but also on the individual human using them. There is no doubt that even very simple models can be useful for knowledge transmission, as the mental processes of accommodation and adjustment can make a connection between the abstract and necessarily limited model and the contingent reality. If this were not the case, the process of knowledge transmission would not be possible. In some sense, our analysis could be considered complementary to Levins's (1966) 'strategy of model building in population biology', although focused more in the 'physical representation' of real objects than in the conceptual construction of models of biological processes.

The main characteristics that make a model didactically useful are: (a) realism and fidelity to the original; (b) proportionality in topological and spatial relationships; (c) detail and resolution; and (d) structural mobility. Each of these characteristics refers to a property of the models and has implications for learning and transmitting knowledge. We provide a brief commentary for each characteristic as it applies to Auzoux's and von Hagens's models.

3.1 *Realism and fidelity to the original*

In Auzoux's clastic models, realism is inherent in their capacity to offer a high degree of similarity to the original in terms of shape, size and colour. In general, models of the entire human body are constructed at normal size, but some isolated organs or organisms are purposely oversized (*see below*). The models show the shape and colour of the original live structure or body, and the model provides the impression of the 'real object'. This is the key to the success of Auzoux's models. As a physician and anatomist, he understood the level of anatomical detail necessary to teach medical students. Auzoux intended his models to be used as introductory materials that would prepare students for the dissection of cadavers as part of medical education.

In the case of von Hagens's models, the original plastinated material requires further processing after fixation and plastination to restore the original colour and appearance of the body or organ. Plastination preserves real tissues and organs, but there is a slight loss of fidelity, because the volume and dimensions are reduced during the process of plastination. Consequently, some organs, such as the liver, may have a mummified appearance in comparison with fresh organs, unless properly treated.

3.2 *Proportionality in topological and spatial relations*

Proportionality in topological and spatial relationships refers to relative positions, but at different scales. Topological relationships are those among different structures in an organ that is composed of different tissues. Spatial relationships are those established among different organs that, when united, offer a representation of the entire organism. The clastic nature of Auzoux's models allows a dynamic relocation of tissues and organs in the organism, making possible the study of both topological and spatial relationships.

In contrast, von Hagens's plastinates generally maintain the topological relationships but not the spatial ones. The latter are usually distorted in order to show anatomical details of structures that are originally hidden. The stiffness of the plastinates makes it impossible to revert to the original spatial relationships.

3.3 *Detail and resolution*

Detail and resolution are limited by the size of the reproduction in Auzoux's models, and different organs and animals receive different levels of detail. For instance, a model of the human ear is magnified seven or ten times to show its internal structure and has been considered a model of the finest quality (Davis and Merzbach 1975). However, the model of the entire human body is similar in size and shape to an average human body. Nevertheless, there is a limit to the resolution of Auzoux's models because they are meant to be observed with the naked eye and because an observation through a microscope would not reveal real tissues but rather the structure of the paper from which they are formed.

In contrast, von Hagens's plastinates, being made from real bodies, are real structures that can be observed under magnification.

3.4 *Structural mobility*

Auzoux's models allow the disassembly and repositioning of various tissues and organs, making a 'virtual dissection' possible. This was the unique aspect of his models, which is still relevant for the teaching of anatomy. As remarked by Rizzolo and Stewart (2006), among the benefits of a real dissection (or simulated dissection in this case) is the developing of 'spatial reasoning skills needed to understand' drawings, images and computer simulations of anatomical materials.

Von Hagens's distinctive display of different body parts visualizes tissues and organs that would otherwise be obscured by others, but there is no possibility of reverting to the original arrangement of the body parts. In this sense, von Hagens's models cannot be used in a complete 'virtual dissection'. Hence, these models facilitate visualization, but not manipulation. As a consequence, the simultaneous presence of several different models is necessary to study different systems, such as the respiratory, circulatory and digestive systems.

3.5 *Extending the utility of the models: texts for students*

The photographic reproduction of anatomical models in textbooks usually improves their pedagogical value and frees the textbook authors from preparing costly original drawings. There is no representative evaluation of the use of Auzoux's models in teaching manuals, although there is some scattered information indicating that they have been used occasionally. William James included a reproduction of the ear model by Auzoux in his introductory textbook on psychology (Davis and Merzbach 1975). In the nineteenth century, the main general text of natural history for secondary school students for 40 years in Spain incorporated reproductions of Auzoux's models, including a clastic man, as the main illustrations (Guerrero 2006) and was awarded

Figure 1. Clastic man by Auzoux. Courtesy: Cardenal Cisneros Institute (Madrid).

a gold medal for teaching books in the Paris Universal Exposition (1878).

However, in spite of the importance that the use of images of models can have for didactic purposes, von Hagens's bodies cannot be photographed and reproduced freely as they benefit from a copyright that limits their extensive use as teaching material. This is a common situation also for many museums and institutions holding anatomical models. The Hunter Museum in London, the Museum of Medical History in Berlin, or the Museum of Zoology and Natural History 'La Specola' in Firenze, to mention just a few, do not allow photographs to be taken of their holdings or exhibitions without special permission. Other natural history museums, such as London's Natural History Museum or the American Museum of Natural History in New York City, do not impose such limitations.

4. A retrospective

Figure 2. Clastic man (detail) by Auzoux. Courtesy: Cardenal Cisneros Institute (Madrid).

Sporadic information on the legacy of Auzoux's models and reproductions, either as models used for teaching zoology students or for demonstrations in medical schools, are appearing in disparate sources after decades of oblivion (USA: Bissell 1960; Stullich and Bryant 2005; Cuba: Valero and Garcia 1999; México: Suárez 2003; Japan: Tsukisawa 2007; Chile: Valenzuela 2007; England: Bates 2008; Australia: Campbell 2004). Curiously enough, a recent paper by Duran *et al.* (2009) reviewed the use of *papier-mâché* models of animals in elementary schools without mentioning Auzoux's work.

In our case, the clastic models illustrated in this paper (figures 1–3) were acquired by the Instituto Cardenal Cisneros in Madrid in 1845 after the incorporation of natural history as a subject in the secondary school curriculum. Despite the novelty of this discipline at that time, the difficulties associated with its teaching and, above all, the scarcity of resources, caused Professor Manuel Galdo (1825–1895) to obtain permission and 2000 pesetas (the equivalent of 11 500 present-day Euros) from the Spanish Government to purchase a set of clastic animal and human models, some of which are shown in figures 1–3. Professor Galdo (1878) used the clastic models for over forty years to teach natural history in his daily fifth-grade classes that

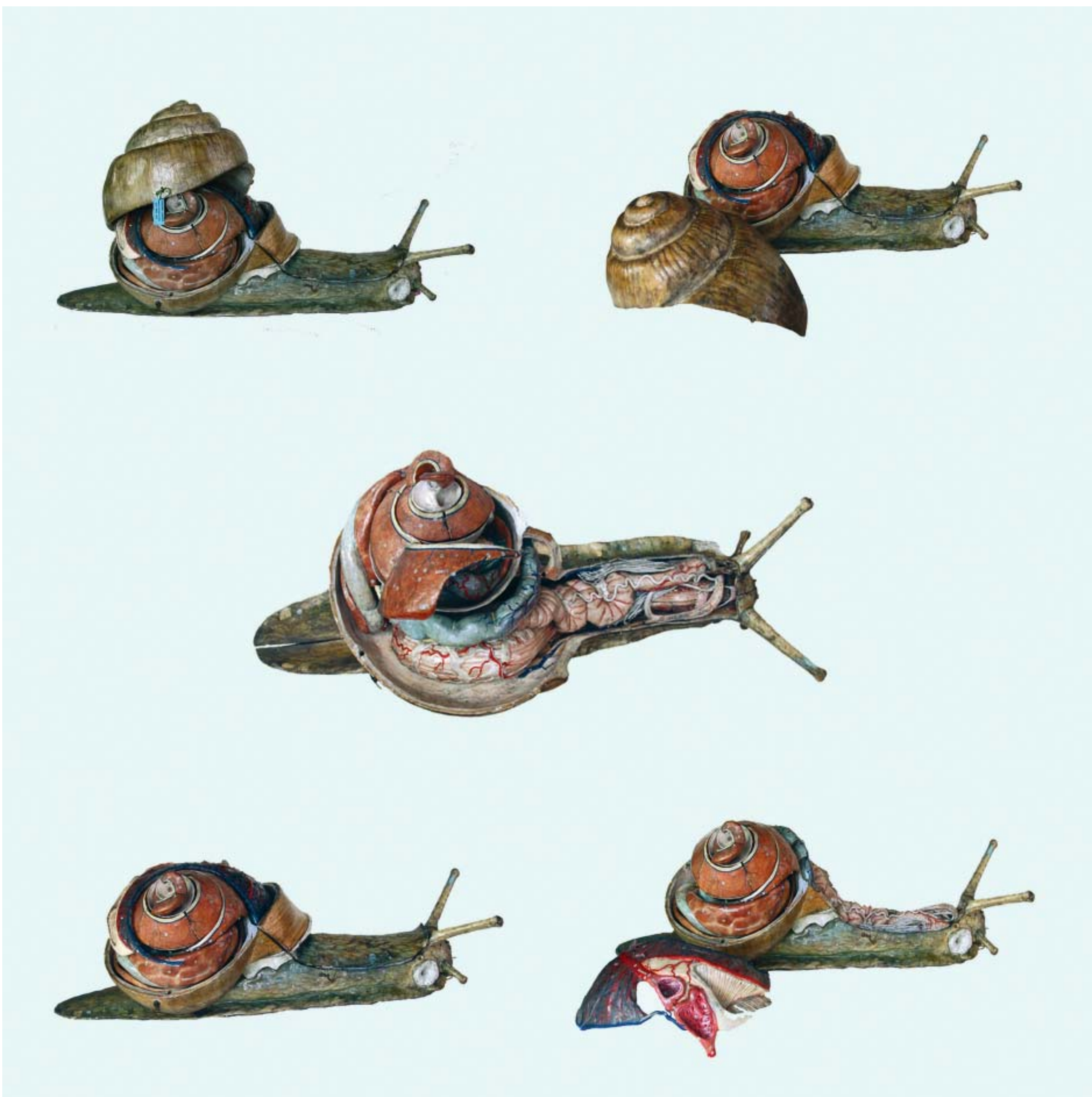

Figure 3. Sequential 'dissection' of a snail. Courtesy: Cardenal Cisneros Institute (Madrid).

lasted one-and-a-half hours each. In so doing, he attempted to present science as an exciting approach to seeing Nature, a goal that was greatly facilitated by the use of the clastic models of Dr Auzoux.

5. Conclusion

There is a growing interest in Auzoux's models and legacy. An international conference on anatomical models was held at the Museum Boerhaave (Leiden) in November 2008 to commemorate the completion of restoration of the collection of models by Dr Auzoux (*https://www.h-net.org/announce/show.cgi?ID=164151*, accessed 10 July 2009). The main lesson derived from Auzoux's models is that to reach a deeper understanding of a phenomenon or an object, one has to be able to reconstruct it in one's mind or in actuality, for example, by repeating it in the laboratory, obtaining similar results with an experimental design in the field, or by reconstructing the physical appearance of an original object. Auzoux had apparently realized that observation was important, but not sufficient to retain knowledge: one needs to be able to reconstruct an object from its individual components. The merit of his approach lies in the fact that his clastic models permit an interaction with the object of study, which preserves the essence of the dissection class. Similarly, with von Hagens's technique, there is a tendency to include plastinated material in anatomy courses hand-in-hand with cadavers preserved in formaldehyde. In a recent survey of 149 students of neuroanatomy, the preference for plastinates was due not only to their odourless and easily manipulated nature, but due to their realism as compared with formaldehyde-preserved cadavers (Roda-Murillo *et al.* 2006). In both cases, and as has recently been discussed by Rizzolo and Stewart (2006), problem-solving dissection helps to develop habits of mind for clinical practice, as well as spatial reasoning skills needed to understand computer simulations and interpret imaging data.

What is applicable to the learning of a specific subject such as anatomy through the use of models could be extended to other subjects and generalized to museums and exhibitions. No matter how many visualizations or explanations are given to students about, for instance, a molecular laboratory or a similar subject, a hands-on approach and experience provide nuances that a virtual world cannot provide. There is a power in the physical interaction with the material of study that simple observation, even supported by new technologies, such as video and computer simulation, cannot match. Implicit in the interaction with models and other real objects is what can be called the 'kinaesthesia' of knowledge; that is, the additional information that we obtain through the position and movement of our muscles and the whole body. For instance, looking at an object on a screen is quite different from interacting with the model through touching it or just having to move our head or body backwards or forwards to fully appreciate the size, weight and location of the real object. In this sense, we can conclude that genuine perception is beyond the power of the eye.

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http://www.abdn.ac.uk/~nhi708/treasures/auzoux.php. Aberdeen University Zoology Museum has a detailed web page on Auzoux life and work (accessed 10 July 2009)

The French Digital Library, Gallica (*http://gallica.bnf.fr/*), is a fantastic source for text relative to Auzoux and is freely available

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