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Armadillos under the Microscope: The End of Natural History and the Emergence of Bio-Materials Research

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ABSTRACT

In the nineteenth century, an animal from the Americas known as the armadillo offered an extraordinary subject for zoologists engaged in the study of the outer covering of four-limbed vertebrates and its components. The armadillo, a cuirassed living mammal, had excited the curiosity of European naturalists since the early sixteenth century, and their shells had thus become a common sight in collections. The armadillo's carapace provided a structure that could be scrutinized in order to understand animal materials, one that afforded the use of microscopes and chemistry in the emerging life sciences that tried to understand the relationship between form and function and the chemical composition of animated matter. The carapace of the armadillo moved from the culture of curiosity in which it was first collected into the new field of animal chemistry, a key move that is crucial for historians to understand the emergence of the study of animal materials. Armadillos accompanied the expansion of chemistry, microscopy, and physics as they were used to study the materials that constituted the mammals' dermal coverings. This paper mines nineteenth-century publications for episodes connected to the long story of the study of this shell's anatomical and chemical contrivances, and the crucial role it played both in the emergence of new scientific knowledge and in the discovery of new bio-inspired materials still derived from this animal today. This paper is part of a special issue entitled "Making Animal Materials in Time," edited by Laurence Douny and Lisa Onaga.

KEY WORDS: biomaterial sciences, animal chemistry, armadillos, tessellated materials, mammal systematics, museum collections

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INTRODUCTION

Living armadillos are placental mammals. They are endemic to Central and South America with the exception of the nine-banded armadillo, which is rapidly expanding its range in North America. Spaniards named the animal "armadillo" on account of its armor—that is, its carapace or shell. In Brazil and France, they were called *tat(o)u*, but in the Americas they are known as *quirquincho*, *encubertados*, *pichi*, or *peludo*.[1] Their shell is formed by plates of dermal bone covered in relatively small, overlapping, epidermal scales. This tessellated structure is accompanied by wiry hairs on their sides and belly, except for some species, such as the *peludo*, or big hairy armadillo, whose scientific and common names are clearly derived from the hair densely covering its underside, as well as the long, coarse hairs projecting from the bony plates of its back.

Animals such as armadillos provided nineteenth-century researchers with the material basis from which to investigate questions regarding mammalian natural history, chemistry, and evolution, specifically with reference to skin, hair, and scales. The importance of these experiments on such animal materials during this period remains understudied. As Peter Fratzl and Steve Weiner said more than a decade ago, material scientists "should be 'mining' the huge reservoir of knowledge on natural materials for good ideas to be translated into the engineering world."[2] This paper is partly a historiographical response to this call.

The armadillos and their shells were a common feature in European curiosity cabinets and have excited the curiosity of naturalists since the sixteenth century. Numerous historians of science and culture have discussed the armadillos' place in collections, the ways in which Western scholars have interpreted them, their representations as an emblem of the Americas, and their use for making remedies in Renaissance medicine.[3] However, less well known is the

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[1] Irina Podgorny, "Los conejos de calabaza," *El mundo atlántico y la modernidad iberoamericana 1750–1850,* vol. 1 (México: RGM, 2012), 222–37.

[2] Peter Fratzl and Steve Weiner, "Bio-Inspired Materials—Mining the Old Literature for New Ideas," *Advanced Materials* 22 (2010): 4547–4750. doi:10.1002/adma.201002127

[3] Florike Egmond and Peter Mason, "Armadillos in Unlikely Places. Some Unpublished Sixteenth-Century Sources for New World 'Rezeptionsgeschichte' in Northern Europe," *Ibero-amerikanisches Archiv* 20, no. 1/2 (1994): 3–52; Ernesto Capanna, "South American Mammal Diversity and Hernández's Novae Hispaniae Thesaurus," *Rendiconti Lincei* 20, (2009): 39–60; Podgorny, "Los conejos de calabaza" (n.1); Simon Varey, *The Mexican Treasury: The Writings of Dr. Francisco Hernández* (Stanford, CA: Stanford University Press, 2000); José María López

early nineteenth-century afterlife of the materials collected in the frame of the so-called Early modern "culture of curiosity": in the nineteenth century, with the dawn of this culture, thanks to their relative incorruptibility, far from disappearing, the carapaces moved from curiosity cabinet to laboratory. There, chemists, anatomists, and naturalists experimented on the properties of this peculiar dermal covering to elucidate its components. Indeed, the armadillo's shell offered an extraordinary material to nineteenth-century zoologists engaged in the study of the outer covering of four-limbed animals. As this paper shows, naturalists and pharmacists developed processes and devices for making the tissue of the armadillo legible for microscopy as well as for reducing its component to the chemical elements that, in the end, were the materials of life. Armadillos are the only living mammals to have a hard outer shell made up of bony external plates that are overlaid with scales. This made dried armadillo carapaces or stuffed specimens easy to preserve and transport. The shell of the armadillo landed in the chemical laboratory, another "unlikely place"—the term Egmond and Mason have employed when describing the presence of armadillos in early modern Europe.[4]

In the nineteenth century, the Americas and Europe offered naturalists opportunities to ask questions about, and seek answers to, how mammalian structures related to each other at the micro-scale level. Research into this topic was filtered through emerging intellectual frameworks, particularly the Swedish and French schools of inorganic and organic chemistry and the comparative anatomy that Richard Owen (1804–1892) transmitted in his London Hunterian lectures in the 1840s. At the same time, researchers enthusiastically subjected armadillo carapaces, an unusual animal from the European perspective, to novel chemical inquiry, burning and dissolving some of the many remains from museum collections in an effort to ascertain their chemical compositions. Here, the biomaterial durability of the armadillo's carapace was critical: because it had endured across time and space, relatively unchanged, it was available for such studies. Osteodermatological remains are less ephemeral than hair—their durability made the armadillo an ideal organism on which to study the anatomy and structure of bone and hair. Evidence of the efforts made to subject carapaces from natural history museums to microscopy and chemical analysis remains in the notes and publications, along with the accurate and

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Piñero, *El códice Pomar (ca. 1590), el interés de Felipe II por la historia natural y la expedición* Hernández *a América* (Valencia: Universidad de Valencia-CSIC, 1990).

[4] Egmond and Mason, "Armadillos in Unlikely Places" (n.3).

inaccurate results from the chemical experiments. These experiments resulted in a wide range of theorizing, sourcing of specimens, and modes of inquiry that made these unusual creatures a protagonist in many different domains.

By the late 1840s, the armadillo's shell was being analyzed under the microscope in three apparently disconnected settings. These analyses, we contend, were all related to the emergence and adoption of relatively new scientific techniques and procedures, namely the study of the physical structure and chemical composition of the mammals' tegumentary elements. In order to elucidate this process, this paper presents the Philadelphia studies connected to the invention of an instrument called the "trichometer" for measuring the ductility, elasticity, and tenacity of hair, wool, and fur. The paper then moves to the German and Swiss laboratories, where the analysis of the chemical constituents and physics of the armadillo's shell was employed to explore its potential industrial use. Finally, we show how the microscopic observations of the armadillo's shell revealed that its armor had the same elements that constitute mammalian skin and opened new avenues of inquiry for evolutionary and embryological studies at the turn of the twentieth century.

ARMADILLO: AN ANIMAL UNDER THE MICROSCOPE

As Harold Cook, Paula de Vos, and José Maria López Piñero have emphasized, natural history became a pivot in Spain's pursuit of colonial wealth due to the potential use of plants, animals, and minerals for materia medica.[5] The interest in nature—animals included—was not uncommon among European physicians and apothecaries; it was part of the art of curing disease within a context where nature was considered "the pharmacy of God." Thus, any description of plants, animals, and minerals included their uses, a practice that was transferred to the "New World," where the observation of nature was combined with the study of local medical knowledge. In the Spanish Monarchy, this was part of a model that combined the search for state support, science, and commercial aims.[6] In this context, the animals from the Americas became the

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[5] Harold J. Cook, *Matters of Exchange. Commerce, Medicine, and Science in the Dutch Golden Age* (New Haven, CT: Yale University Press, 2007); Paula S. De Vos, *Compound Remedies: Galenic Pharmacy from the Ancient Mediterranean to New Spain* (Pittsburgh: University of Pittsburgh Press, 2021), López Piñero, *El códice* (n.3)

[6] Arndt Brendecke, *Imperio e información. Funciones del saber en el dominio colonial español* (Madrid / Frankfurt: Iberoamericana-Vervuert, 2012).

source of remedies for old and new illnesses: in the armadillo's case, its shell was marketed in Europe as a remedy the local population used to treat syphilis, whose first recorded European outbreak occurred in 1494–1495. The curative virtues of armadillo, however, would later disappear from European pharmacopeias, though the shells continued to be collected and displayed in pharmacies and cabinets alike.

The armadillo became the iconic animal for the American continent, represented in tapestry, sculpture, engraving, and painting as an attribute of the "New World." Its carapace soon became a subject of curiosity and amazement. Meanwhile, in South America, the armadillo's shell was adapted to build the soundbox of a string instrument known as the "charango."

In the context of late eighteenth- and early nineteenth-century taxonomic debates, some naturalists used the external appearance of the armadillo's shell as an element with which to classify the different species found in the Americas and as a standard of comparison for the shells of other animal groups.[7] French anatomist Georges Cuvier stated that "the species may be almost distinguished by the number of their intermediate bands combined with the form of their compartments; the bands nevertheless are subject to vary one or two according to the individuals."[8]

The *London Encyclopedia* (1829) presented *Dasypus* as a mammal covered with a hard-bony shell that intersected with distinct moveable zones or belts on its head, neck, back, and flanks. This shell extended to the extremity of the tail, whereas its throat, breast, and belly were covered with a whitish coarse-grained skin, resembling that of a hen after its feathers had been plucked. The shell did not consist of one entire piece as in the case of turtles; on the contrary, the belts were connected to each other by membranes, which enabled the animal to move and—in some species—to roll itself up like a hedgehog.

This article from the *London Encyclopedia* reflected, in fact, a subtle development: by 1830, shells had been introduced to the chemistry laboratory, where the analysis of the coverings showed that, while the shell of the Chelonians was a corneous enlargement of the osseous structure intimately united with the rest of the skeleton, in the armadillo it was entirely tegumentary, composed of carbonate and phosphate of lime deposited in cells of animal

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[7] Irina Podgorny, "Fossil Dealers, the Practices of Comparative Anatomy and British Diplomacy in Latin America, 1820–1840," *The British Journal for the History of Science* 46, no. 4 (2013): 647–74.

[8] Georges Cuvier, *The Animal Kingdom Arranged in Conformity with Its Organization*, vol. 3 (London: Geo. B. Whittaker, 1827), 256.

matter, composing a tessellated structure.[9] Previously, the armadillo's shell had been analyzed only in its external appearance, namely in terms of the number of colored belts present in the carapace, a characteristic used for determining the species. This use became obsolete when zoologists realized that the bands could vary among individuals of the same species.

In the context of nineteenth-century comparative/analytical practices—so well characterized by Pickstone in his seminal 1994 article on "museological sciences"[10]—scientists put the shell of the armadillo under the microscope. The shell was defined as a resistant and flexible covering, as well as a successful anatomical characteristic in terms of adaptation: anatomists wanted to go beyond the opacity of the "scales" to understand their chemical constitution. Thus, armadillo shells kept in collections were moved into the chemistry laboratory. This movement marks one of the consequences of the process that Wolf Lepenies called "the end of natural history,"[11] which, in the case of the armadillo, can be described as the transfer of animals from the *materia medica* and natural history cabinets to animal chemistry.

THE CHEMISTRY OF MAMMALS

Using a microscope to observe hair, skin, and scales was far from a novelty: since its adoption in anatomy studies during the second half of the seventeenth century, everything had passed under the lens of a microscope. New to the early nineteenth century, however, was the science of "animal chemistry," or the chemistry of the animal body, as proposed by Swedish chemist and mineralogist Jöns Japop Berzelius (1779–1848). In this new context—as Scott Gilbert relates in this issue—the living organism emerges as something biologically and technologically reconfigured that can be recognized as an animal material.[12]

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[9] Peter Browne and Montroville Dickeson, *Trichographia mammalium; or, Descriptions and Drawings of the Hairs of the Mammalia, Made with the Aid of the Microscope* (Philadelphia: J.H. Jones, 1848), 9; *The London Encyclopaedia* (London, 1829), s.v. "Dasypus," vol. 7, *Cutlery to Elasticity* (London, 1829), 72–73.

[10] John V. Pickstone, "Museological Science? The Place of the Analytical/Comparative in Nineteenth-Century Science, Technology and Medicine," *History of Science* 32, no. 2 (1994): 111–138.

[11] Wolf Lepenies, *Das Ende der Naturgeschichte: Wandel kultureller Selbstverständlichkeiten in den Wissenschaften des 18. und 19. Jahrhunderts* (München: Hanser, 1976).

[12] Scott F. Gilbert, "Shells, Gills, and Gonads: On the Remarkable Persistence of Oysters in the Chesapeake Bay," this issue.

According to Berzelius, the constituent parts of an animal's body were exactly the same as those found in unorganized matter, and they return to their original inorganic state by degrees, partly during the progress of life, and partly after death.[13] Early in the nineteenth century, animal matter was therefore put under the microscope after being reduced to an inorganic state by dissolving, boiling, or burning pieces of flesh, hair, bone, and muscles. These are the same processes that historian Sarah Lowengard mentions in her article on animal fat in this issue.[14] Pharmacists, naturalists, and zoologists not only began to perceive the study of the chemistry of animals as the key methodology to understanding animal physiology and life, but also as a way to exploit animal matter in industry.

Berzelius's proposals were adopted, for instance, to compare the chemical composition of human bones with those of different animals. This gave new meanings to the animals kept in the natural history cabinets, in a process through which they were transformed into the subject of chemical experiments, a process occurring in different settings, wherever people were interested in elucidating the peculiarities of animal matter. Animals collected in other scientific traditions and displayed for other purposes, far from disappearing, continued to be used, thanks in part to the possibilities they offered for answering these new questions and pursuits.

In 1800, C. Merat-Guillot (1776–1826), a pharmacist from the city of Auxerre in Burgundy, published an article on the subject that was soon translated into English. The results, however, were judged as inaccurate. At stake was whether or not the bones of humans and mammals were of a nature different from those of reptiles and fish. Merat-Guillot included hair, corneous substances, and bristles from different animals in his analysis; his list enumerated human bones from a burial ground, dry human bones, bones of an ox, a calf, a horse, an elephant (ivory), a sheep, an elk, a swine, a hare, a hen, a pike, a carp, a viper, horns of a stag, egg and lobster shells, mother of pearl, crab's eyes, white coral, red coral, articulated coralline, and cuttlefish bones, namely the elements collected in the pharmacies of his day.[15] Merat-Guillot had in fact

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[13] Jöns Jakob Berzelius, *A View of the Progress and Present State of Animal Chemistry* (London: J. Skriven, 1813), 2.

[14] Sarah Lowengard, "On the Disappearance of the Animal Body: Animal Fat, Tallow, Candles, Soap, and Chemistry before 1830," this issue.

[15] C. Merat-Guillot, "Comparative Analysis of Human Bones, and Those of Different Animals," *Philosophical Magazine,* volume 7 (1800): 131–34. On oysters, see Scott F. Gilbert (n.12), on the elk, see Irina Podgorny, "The Elk, the Ass, the Tapir, Their Hooves, and the Falling

followed Buffon's advice to collect objects of every kind, study their nature and, from their relations, deduce information to increase knowledge. This is another good example of how Buffon, the epitome of natural history, was being used in a completely different scientific framework—that is, in the laboratory of organic chemistry and the emerging life sciences. This shift to the comparative study of organic materiality would transform the natural history collection into a collection of potential bio-materials.

The questions posed in those experiments, namely the chemical constitution of human and animal tegument, reappeared in 1806, when French professor Louis Nicolas Vauquelin (1763–1826) reported on his experiments to elucidate the animal matter and the chemical composition of hair.[16] He asserted that human hair, the epidermis, nails, horns, wool, and hair in general were all formed from the same animal tissue.

By that period, it had been established that the close resemblance of the intimate structure and chemical composition between true teeth and bones and osseus tissue was not confined to the endoskeleton. The class of tissues in which teeth and scales should rank was the subject of controversy in systems of histology, overlooking the fact that they did not have the same unity of composition as bones. One constituent of teeth, viz. the dentine or ivory, was still being described in the late 1830 as being like hair, arranged in concentric layers when, on the contrary, it bore a close structural resemblance to bone and was almost identical to bone in chemical composition.[17] The relation of teeth to the so-called corneous tissue was unclear in humans, but some believed it was well established in the lower classes of animals, where transitional or intermediate structures between teeth and nails, horns, and hair had been postulated. This was a subject of debate, and the frame in which the study of armadillo shells entered the scene.

The microscopes allied to these chemistry experiments on bio-materials were also linked to the precision of the devices being constructed and used

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Sickness: A Story of Substitution and Animal Medical Substances," *Journal of Global History,* 13, no. 1 (2018): 46–68.

[16] Vauquelin found that hair contained considerable sulphur, and that white, blond, and red hair contained more sulphur than black hair, see Louis N. Vauquelin, "Extrait d'une mémoire sur les cheveaux," *Annales de chimie et de physique* 58 (1806): 41–53.

[17] Richard Owen, *Odontography; or, A Treatise on the Comparative Anatomy of the Teeth; Their Physiological Relations, Mode of Development, and Microscopic Structure, in the Vertebrate Animals* (London: H. Baillière, 1840–45), xxi–xxii; on ivory, see Marianna Szczygielska, "Reading Teeth: Ivory as an Artifact of Classed Whiteness," this issue.

in the German countries and, more importantly, to the observation of how animal materials reacted to changing chemical solutions in a context where chemistry pervaded the study of nature. Zoologists decided to repurpose the microscope as a taxonomic instrument that could be used to determine animal affinities as they were "observed" at the microscopic level of animal matter. For instance, in the late 1830s, Owen examined vertebrate teeth under the microscope in an attempt to find the internal structure that would allow for the classification of vertebrates, coordinating comparative anatomy with recent advances in chemistry.[18] At that time, views about the structure and development of the epidermal appendages, teeth, and the tegumentary system were considered key to understanding their place in the system of tissues, their physiological relations, and their value as zoological characteristics. This was one of the goals of the experiments and devices presented in 1848 in Philadelphia.

THE HARD MANTLED-MAMMALS:A CLASSIFICATION MADE IN PHILADELPHIA

In 1848, Peter A. Browne (1782–1860), a Philadelphia lawyer and naturalist, and the physician and archaeologist Montroville Wilson Dickeson (1810–1882) joined efforts to publish *Trichographia mammalium.* This work consisted of a series of booklets in which they described and drafted samples of hair and mammal coverings they had put under the microscope, "this powerful means of investigation, without the help of which one can no longer speak about any body without being cautious."[19]

While Dickeson was an expert in microscopy in his own right, Browne envisaged building a national collection of mammal hair, including U.S. presidents and armadillos.[20] This ambition had its origin in an interest in sheep's

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[18] Owen, *Odontography* (n.17).

[19] This quote, used by Browne and Dickeson, was taken from Louis Mandl, *Traité pratique du Microscope, et de son emploi dans l'étude des corps organisés* (Paris: Baillère, 1839), a popular manual intended to popularize the contents published in German books related to microscopy. Mandl, a professor of medicine in Paris, summarized the state of the art with regard to the observation of animal hair, skin, and scales.

[20] See Robert McCracken Peck, *Specimens of Hair: The Curious Collection of Peter A. Browne* (New York: Blast Books, 2018) and Richard Veit, "A Case of Archaeological Amnesia: A Contextual Biography of Montroville Wilson Dickeson (1810–1882), Early American Archaeologist," *Archaeology of Eastern North America* 25 (1997): 97–123.

wool following the model set by Saxony, where the government aided in the improvement of sheep breeds.[21] According to different reports, in Saxony, when the lambs were weaned, each was placed upon a table to minutely observe its wool and its form. The finest animals were selected for breeding, the rest being condemned. Browne and Dickeson wanted to speed these improvements by inventing new devices and methods that combined organic chemistry, microscopy, and zoological taxonomy. This would reduce to "absolute certainty" the properties used in the wooly fiber trade—ductility, elasticity, and tenacity.

Browne and Dickeson examined the samples of hair, wool, and fur, the tegumentary appendages that in their view still required serious scrutiny and a better understanding of their organic structure. They proposed examining the structure of "each hair," an investigation they thought might prove useful to medical practitioners for their treatment of skin illnesses: skin and hair were so intimately connected that the former could not be understood without knowledge of the latter. Moreover, hair, wool, and fur were objects of utility in manufacture, so their study could help to increase the wealth of the American population. And in fact, their investigations contributed greatly to commercial wool production.[22]

Unsurprisingly, hatters, furriers, wool dealers, and staplers joined physicians to celebrate the invention of the trichometer, a combination of the microscope and micrometer. Browne and Dickeson envisioned their instrument as a means to analyze the properties of mammalian hair. Browne presented the trichometer, together with the first issue of *Trichographia mammalium*, as a way to request funding for the publication of the complete series. The first booklet started with the least useful mammal, at least from the wool dealers' point of view: the armadillo, which, however, allowed the authors to propose a new classification based on the chemical composition of what they called "tegumentary appendages."

Browne and Dickeson graded mammals according to the property of their wool (or hair), which the microscope had revealed to be the foundation of the art of felting. In 1835, an English veterinarian discovered that every fiber of wool featured rough projections that interlocked during the process of felting,

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[21] Eric C. Stoykovich, "The Culture of Improvement in the Early Republic: Domestic Livestock, Animal Breeding, and Philadelphia's Urban Gentlemen, 1820–1860," *The Pennsylvania Magazine of History and Biography* 134, no. 1 (2010): 31–58.

[22] Peck, *Specimens of Hair* (n.20).

thereby binding the strands together to form one compact mass.[23] Browne and Dickeson followed up this discovery with new devices, allowing them to ascertain that scales surrounded the circumference of each fiber. They discovered how to determine which wool had no felting property, or possessed it in an insignificant degree. The hard armadillo shell (with its hairs) afforded Browne and Dickeson a model to demonstrate how their procedures, instruments, and observational practices dissolved the visible and touchable tegumentary structures into precipitations, solutions, and measurements of the tensile strength of individual filaments, providing a precise overview of the properties of hair and fleece.

In this new classification, armadillos became "mammals with a hard mantle; composed of carbonate and phosphate of the lime deposited in cells of animal matter." The other mammal groups were defined by fibrous corneous protuberances, fibrous and parenchymatous matter, membranous and scale-like matter, and fibrous corneous matter covered with membrane, namely hair (bristles and non-agglutinated fibers: hair, fur, and wool). According to Browne and Dickeson, corneous matter was distinguished from bony matter by the absence of bone-earth (phosphate of lime) and from feathery matter, to which it was closely allied.[24]

Browne and Dickeson were not interested in solving the question of why nature placed the armor upon the armadillos' body and head. However, they recalled that one writer had expounded on the providential protection it afforded from the otherwise destructive effects of South American ants, forgetting that these insects could still attack the unprotected abdomen. Another author had suggested that the armor was designed to shield the animal from the scorching effect of a tropical sun, not paying attention to their subterranean habits. In citing these opinions, they showed their disdain toward teleological assumptions regarding the functions of the structures they were studying (figure 1).

In Browne and Dickeson's experiments, they placed fragments of the armadillo's armor into diluted muriatic acid, which made it become as flexible as a piece of leather. The lime was dissolved with effervescence. The experiment continued, and from it they concluded that the armor was composed of carbonate and phosphate of lime and animal matter in equal quantities.

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[23] William Youatt, *Sheep, Their Breeds, Management, and Diseases* (London: Baldwin and Cradock, 1837).

[24] Browne and Dickeson, *Trichographia mammalium* (n.9), 5–6.

Fig. 1.

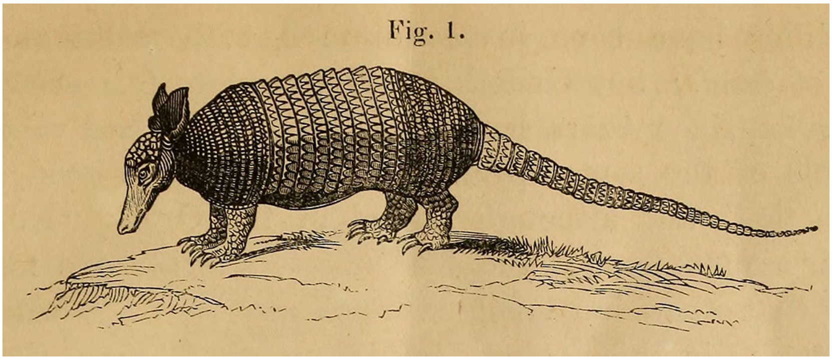

FIGURE 1. Armadillo, from Browne and Dickeson, *Trichographia mammalium* (n.9). The drawing is based on the daguerreotype of the mounted skeleton of a South American seven-banded armadillo (*Dasypus septemcinctus*) loaned in 1848 from Paul Beck Goddard (1811–1866).

Browne and Dickeson were following the example set by Saxon breeders as well as replicating step by step, name by name, the procedures and classification system set out by German apothecary and physician Joseph Franz Simon (1807–1843), whose work "Animal Chemistry with Reference to the Physiology and Pathology of Man" had been translated into English in 1845.[25] Simon had divided the constituents of the animal body into two great classes: mineral and organic, both of which included several subdivisions and were presented as a collection of useful bio-materials. Minerals were divided into those of service in the animal body; those that affected important objects in the system by their chemical actions; and those that may be eliminated without exerting any unfavorable effect. The first subdivision included water and phosphate of lime, whose importance ranked next to water and occurred in bone, blood, milk, urine, and feces; the second subdivision included carbonate of lime, forming the principal part of the skeleton in invertebrates and in a greater or lesser proportion in the bones of higher animals; and the third subdivision included phosphate of magnesia, as well as all the constituents that Browne and Dickeson were trying to identify in the shell of the armadillo. Moreover, the Americans compared their results with the data added to Simon's book by the translator, namely German chemist Ernst von Bibra (1806–1878), who in 1844 published his "Chemical Research on the Bones and Teeth of Humans and Other Vertebrates." In that book, von Bibra analyzed the armor of *Dasypus*

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[25] Johann Simon, *Animal Chemistry with Reference to the Physiology and Pathology of Man* (London: Sydenham Society, 1845).

niger (nine-banded armadillo), remarking that only the bony armor of the animal consisting of scales was at his disposal and that he had discovered that the bony plates not far from the neck, the belt, and the tail, as well as the horn substance, did not all have the same composition.[26]

INDUSTRIAL USES OF THE ARMADILLO SHELL

By the late 1840s, zoologists and chemists alike were intrigued by the chemical constituents of the armadillo's shell. Some of them regarded its potential uses and were attracted by the possibilities opened up by chemistry and microscopes. In 1860, the German agricultural chemist Wilhelm Wicke (1828–1871) analyzed the ash of the bony plates from the armadillo's scales and caudal vertebra, confirming that the plates behaved just like bone during cremation.[27] His results, as modest as they appeared, were replicated in most journals devoted to applied chemistry, which were at that time publishing or listing all the results of those studies that incinerated animal bones to analyze their chemical reactions to acids and salts. These procedures have to be understood in the framework of investigations about the potentiality of bones in the new industry of chemical fertilizers. Instead of merely discarding carcasses from slaughterhouses as rubbish, it was thought that they could be of some use in the nascent fertilizer industry. Recycling the discarded remains of dead animals and their excrements became part of a chemical industry eager to find valuable materials in the organic world.[28] The interest generated by the chemical components of armadillo shells—as transportable and abundant as they were—seems to suggest they were being considered for such endeavors.

Wicke recognized that his work from 1860 on was just a "chemical" confirmation of the histological research done earlier by German anatomist Georg Hermann von Meyer (1815–1892), the extraordinary professor at Zürich University. In 1847, von Meyer had reported to the Swiss Society of Naturalists on his studies of the skin of the *Euphractus/Dasypus sexcinctus* (six-banded

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[26] Ernst von Bibra, *Chemische Untersuchungen über die Knochen und Zähne des Menschen und der Wirbelthiere* (Schweinfurt: Kunstverlag, 1844), 123.

[27] Wilhelm Wicke, "Analyse der Schuppen vom Gürtelthier," *Annalen der Chemie und Pharmacie* 37, no. 2 (1860): 251–52.

[28] Gregory Cushman, *Guano and the Opening of the Pacific World: A Global Ecological History* (New York: Cambridge University Press, 2013); Irina Podgorny, "Recyclen: Vom Schrott der Ausrottung zur Ökonomie der (Sub-)Fossilien," in *Sammlungsökonomien: Vom Wert wissenschaftlicher Dinge*, ed. Nils Güttler and Ina Heumann (Berlin: Kadmos, 2016), 23–46.

armadillo), and more generally on the histology and architecture of the shell.[29] Von Meyer's microscopic observation of the armadillo shell had revealed that the armor consisted of the usual skin elements: dermis, papillary body, and epidermis. In the substance of the dermis were plates of real bone with bone corpuscles embedded, so the substance of the dermis was partly on the inner, partly on the outer side of the bone plates, but partly also between them. Wicke's analysis showed that von Meyer was right and that, chemically speaking, the plates behaved like bones.

In von Meyer's histological observations, he detailed how each bone plate showed a thick bone substance on its outer surface and a spongy bone substance on its inner surface, a structure that he went on to study in his 1867 work on the functional structure of the *spongiosa.* Strictly speaking, the bony plates of the carapace were more or less regularly hexagonal. Von Meyer continues: the bone plates of both the last row before the girdles and the first row after the girdles showed transitional forms and, on their side, facing the girdles, had the same characteristics as the girdle bones, but on the side facing the carapace they were the same as the carapace bones. The armor plates were placed next to each other with straight cut edges; the plates of the individual belts lined up with just such edges, and the belts, all joined to each other. Von Meyer concluded that the peculiarity of the armadillo's skin construction granted the animal a protective cover, while the movable belts allowed for mobility in addition to this protection.

In Zürich, von Meyer developed a program of research that connected the study of the structure of mammal skeletons (especially the human one) with what he called "the architecture or engineering of the bones." He used physics and mathematics to determine lines of strength, resistance, and tension as factors related to movement, flexibility, and protection. His study of the skin and carapace of the six-banded armadillo must be understood as part of his interest in the materials, connection tissues, types of bones and bony materials that composed the skeleton, and the surfaces and imbrication that created a particular covering that was both rigid and flexible at the same time. The armadillo reappeared in von Meyer's book *Die Statik und Mechanik des menschlichen Knochengerüste*s (The Statics and Mechanics of the Human Skeleton, 1873), published when he was director of the Anatomical Institute of Zürich. He was interested in the mechanics of movements and the

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[29] Georg Hermann von Meyer, "Über den Bau der Haut von Dasypus und der Stacheln von Raja," *Mittheilungen der Naturforschenden Gesellschaft in Zürich* 6 (1847): 87–92, on 87–88.

mechanical structure of the skeleton. In this frame, armadillos—as fossorial animals—offered him a good case study with which to demonstrate that the bony material was strongest in the parts of the skeleton that required it, considering the peculiar habits of that animal.[30]

Von Meyer, however, made no mention of the armadillo in his popular and controversial pamphlet "The Correct Shape of Shoes" (1858), where he insisted on the importance of the arch and the perfect arrangement of the twenty-six bones that constituted the human foot, each allowing for more or less motion against one another.[31] Von Meyer warned against symmetrical footwear and—contrary to common use in that era—proposed that right and left shoes should be different. Further research could provide some clues about whether or not von Meyer, a functional anatomist, was inspired by his own detailed study of the architecture of the armadillo's shell to conceive shoes that were adapted to the specific architecture of each foot. Like an engineer, von Meyer constructed a new, "rational" shoe sole that was simultaneously protective and flexible, like the armadillo's covering provided by nature.[32]

CONCLUDING REMARKS

Chemists, anatomists, and zoologists were attracted to strange forms dispatched from distant lands through colonial and diplomatic networks, which resisted decay because of their particular material properties. The range of animals that were "put in the test tube" or, in the terms of the time, subjected to strong heat, increased year by year. The American and the German analysis of the armadillo's shield presented in this paper had different goals, but they

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[30] Georg Hermann von Meyer, *Die Statik und Mechanik des menschlichen Knochengerüstes* (Leipzig: Engelmann, 1873). In the 1860s von Meyer had collaborated with Karl Culmann (1821–1881), a structural engineer and mathematician, the author of *Die graphische Statik* (Graphic Statics) (Zürich, 1866) and professor of engineering at the Swiss Federal Institute of Technology (ETH). See J. Skedros and R. Brand, "Biographical Sketch: Georg Hermann von Meyer (1815–1892)," *Clinical Orthopaedics and Related Research* 469, no. 11 (2011): 3072–76. doi:10.1007/s11999-011-2040-6

[31] Georg Hermann von Meyer, *Die richtige Gestalt der Schuhe* (Zürich: Meyer & Zeller, 1858).

[32] Georg Hermann von Meyer, *Why the Shoe Pinches: A Contribution to Applied Anatomy* (New York: Holbrook, 1885); Andreas Mayer, *The Science of Walking: Investigations into Locomotion in the Long Nineteenth Century* (Chicago: University of Chicago Press, 2020); Nike U. Breyer, *Schuhreform, Bewegung, Körperbilder: Umrisse einer Kontroverse des 19. Jahrhunderts* (Gießen: Gießener Elektronische Bibliothek, 2015). http://geb.uni-giessen.de/geb/volltexte/2015/11818

were all related by the expansion in the applications of microscopy and chemical analysis in the field of natural history. Moreover, they showed how animal materials resulted from the cross-breeding of industrial and analytical analysis, old and new scientific traditions. They all shared the conviction that animal materials should be analyzed and compared in terms of the microscopic structures and chemical composition of their anatomical constituents. They were convinced that the chemistry and microscopy of living matter could serve as the basis for more reliable taxonomic classifications and speculated on potential applications of animal materials. Moreover, their endeavors show how materials collected in what was already seen as an old-fashioned scientific tradition were transferred into new inquiries. At the interface of these old materials with the new/old devices, a vision of animals in terms of their chemical components emerged, the "beginning" of bio-materials research.

The study of the structures that characterized armadillos played a key role in these processes. In the years to come, the shell of the armadillo moved again: other scientists used the expertise gained through studies of the histology and chemistry of the armor for the new theory of evolution. In this context, German and Swiss comparative anatomists discussed whether the scaling of extant mammals—such as the armadillo—was inherited from its ancestors or if it was a new acquisition, a topic that still deserves further research but proves how things collected in the most divergent scientific traditions were and can still be reused for crafting and making visible new scientific objects.[33] Nowadays, biomimetic designers are fascinated by this incredible animal that has a natural armor affording flexibility and protection: they are in fact followers of the processes that von Meyer studied in an exemplary way more than a century ago.[34]

Zoologists and chemists found that the armadillo's carapace offered an ideal case study to investigate animal materials and structures. Armadillo shells were abundant both in nature and natural history collections. Thanks to their osteo-dermatologica structure, they resisted decay, were easy to transport and to store, and were considered disposable. The study of the carapace of the armadillo, its abundance, and characteristics accompanied and expedited the expansion of chemistry,microscopy, and physics. The materials and animal

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[33] Max Weber, "Observations on the Origin of Hair and on Scales in Mammals," *The Annals and Magazine of Natural History* 12, no. 67 (1893): 1–11.

[34] Irene H. Chen, James H. Kiang, Victor Correa, Maria I. Lopez, Po-Yu Chen, Joanna McKittrick, and Marc A. Meyers, "Armadillo Armor: Mechanical Testing and Micro-Structural Evaluation," *Journal of the Mechanical Behavior of Biomedical Materials* 4, no. 5 (2011): 713–22.

chemistry that constituted its dermal covering were investigated, as illustrated in the nineteenth-century episodes presented here. The study of the armadillo shell's anatomical and chemical contrivances transformed this unique creature from an early modern curiosity into a laboratory animal. In doing so, American and European scholars could use the armadillo as a medium to propose new classifications of mammals, and to experiment with chemical analysis, agricultural chemistry, sheep breeding, shoe design, and mechanical properties.

Today, the tiled arrangement of the armadillo shell has become a new source of inspiration for the material science community, as demonstrated by the research done by Chen et al.[35] Armadillos are part of the collections of natural history museums all over the world, and their carapaces not only continue to provide materials for the future, as we have shown, but they are also an excellent example of how materials collected in"old-fashioned" scientific traditions have been and can be used in new inquiries.

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[35] Chen et al., "Armadillo Armor"; see also "Tesselated Material Systems" by Felix Rasehorn, a Collaborative Research Project within the Cluster of Excellence "Matters of Activity" (Group integrated by Mason Dean, John Nyakatura, Binru Yang, Nikolai Rosenthal, and Felix Rasehorn). http://forschungskreis.com/project/tessellated-material-systems