NEUENSCHWANDER LECTURE, ESHS 2014

From the History of Science to the History of Knowledge – and Back

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Abstract. The history of science can be better understood against the background of a history of knowledge comprising not only theoretical but also intuitive and practical knowledge. This widening of scope necessitates a more concise definition of the concept of knowledge, relating its cognitive to its material and social dimensions. The history of knowledge comprises the history of institutions in which knowledge is produced and transmitted. This is an essential but hitherto neglected aspect of cultural evolution. Taking this aspect into account one is led to the concept of extended evolution, which integrates the perspectives of niche construction and complex regulative networks. The paper illustrates this concept using four examples: the emergence of language, the Neolithic revolution, the invention of writing and the origin of mechanics.

Keywords. Cultural evolution, extended evolution, history of knowledge, history of science

1. Science as Cultural Practice

Is there a broader lesson to learn from the history of science? Is there a way to understand human history with all its terrifying disasters nevertheless as a potential learning process in which opportunities may have been missed most of the time but still were there for us to grasp? These were some of the questions that originally motivated me when I turned from physics to the history of science. I was neither tired by the rigor of physics nor bored by its technicalities, but was fascinated by its long history reaching deep into antiquity, by the conceptual breaks and the diversity of ideas it harbored, and by its deep connections with human concerns. Neither a purely descriptive historiography nor a philosophical approach with a preconceived notion of rationality, and be that of its denial, seemed to offer answers to my questions. I therefore decided to look for myself, guided by the work of great historians and philosophers of science and in particular by those who became my personal mentors and friends, such as Peter Damerow and Yehuda Elkana.

For many historians of science, science no longer seems distinguishable from other forms of cultural practices. It has ceased to be a paradigm of universal rationality and

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Centaurus 2015: Vol. 57: pp. 37–53; doi:10.1111/1600-0498.12075

presents itself as just one more object of study for cultural history or social anthropology. Even the most fundamental aspects of the classical image of science -- proof, experimentation, data, objectivity or rationality -- have turned out to be deeply historical in nature. This insight has opened up many new perspectives on the study of the history of science, which is turning more and more into a history of knowledge. It thus includes not only academic practices, but also the production and reproduction of knowledge far removed from traditional academic settings, for instance, in artisanal and artistic practices, or even in family and household practices.

To give just one example: much of the knowledge at the core of the Scientific Revolution of the early modern period was the practical knowledge of artisans, engineers, physicians or alchemists. It was by developing and transforming this kind of knowledge, dealing for instance with the motion of projectiles in ballistics or with the transformation of materials in metallurgy, that contemporary scientists such as Galileo made their great discoveries (Renn, Damerow and Rieger, 2001; Valleriani, 2010, 2013).

2. *The Globalization of Knowledge in History*

Perhaps even more importantly, non-Western epistemic practices are now also considered without being immediately gauged against the standards of established Western science. 'On their own terms' is the slogan under which Chinese science is currently being analyzed, without a constant evaluation of what it lacks or does not lack in comparison to Western science (Elman, 2005). Similarly, the worldwide circulation of knowledge is now considered not just as a one-sided colonial or post-colonial diffusion process, but rather as an exchange of knowledge in which each side is active and in which knowledge is shaped as much by dissemination as by appropriation.[1]

In recent years, the migration of knowledge has become an active field of research. With few exceptions, the emphasis has been placed mostly on local histories focusing on detailed studies of political and cultural contexts and emphasize the social construction of science. While this emphasis has been extremely useful in overcoming the traditional grand narratives, and also in highlighting the complexity of these processes and their dependence on specific cultural, social or epistemic contexts, it has led to a somewhat distorted, highly fragmented picture of science.

This picture does little justice to the overwhelming societal, economic and cultural significance of science in a globalized world. Rather than representing one of the major and still unexplained economic and societal forces in the modern world, science dissolves into a plethora of highly localized and contextualized activities, which are scarcely connected to each other. It has become a mark of political correctness to provincialize European science as representing just one among many equally justified points of view within a global culture.

But such well-meaning political correctness does not enable historians and philosophers to compensate for the destruction of indigenous cultures, for the genocides, for the lack of gender equality, in short, for the immense damage and crimes committed in world history in the name of Western rationality and science. The golem of science cannot be tamed by underestimating it, let alone by overestimating our own influence as its witnesses.

But what can we do when we don't want to ascribe the powerful role of science in the modern world, for better or worse, to its intrinsic rationality, to the superiority of a universal scientific method or to some kind of capitalist, technocratic conspiracy responsible for its triumphal procession as a driving force of modernization? Neither piling up local studies, nor offering weaker versions of the original universalist point of view will do. What is needed is a truly global perspective accounting for both the universalizing role of science in today's world and for its ever-shaky claims to rationality on historical grounds. The fragmented picture suggested by current cultural studies has induced us to underestimate the extent to which the world is and has been connected -- for a very long time -- by knowledge.

The widened perspective of a history of knowledge may help us to see a larger picture in which the dilemma of rationality, dependent on historical conditions and yet somehow transcending them, may dissolve. The norms of rationality are indeed arbitrary or rather, historically contingent. But they are part of the lives of human societies, which may thrive or founder also in dependence on the moral and epistemic norms they have chosen. As a society, we may locally and temporarily employ whatever norms and epistemic practices we happen to have established in the course of history.

Ultimately, however, with the growing global connectivity and the planetary impact of our collective actions in the age of the Anthropocene, the totality of these experiences will decide on the fate of the human species.[2] Pursuing certain norms for social behavior and developing or not developing certain knowledge for dealing with our natural and societal environment may eventually lead to our extinction as a species; these were then evidently problematic moral and epistemic norms.

The history of science can only be understood against the background of a global, long-term history of knowledge, including local knowledge that constitutes the substratum and the matrix of all other forms of knowledge. Is there a theoretical perspective from which this claim may be substantiated? In the following I will suggest such a perspective and illustrate it with examples ranging from the origin of humanity to the origins of modern science. This should not be understood, however, as a proposal for a universal theory. It is rather meant to suggest a framework that may allow us to integrate insights from various sources, not only from the many case studies we are all pursuing, but also from the various disciplines that are involved beyond history itself, such as anthropology, sociology, linguistics, philology, archeology, cognitive science and psychology, and many more. We should of course resist any form of reductionism and avoid playing off the cognitive, social and material dimensions of our subject of study against each other.[3]

3. *Knowledge and Cultural Evolution*

Knowledge is encoded experience. Based on experience, it is, at the same time, the capacity of an individual, a group or a society to solve problems and to anticipate appropriate actions. The history of knowledge has traditionally been studied from a restricted perspective that favors innovation over implementation, transmission and transformation. In the past, historians of science and technology have often focused on the question of who was the first to discover a fact that later became a key innovation and when this took place. Much less attention has been paid to the question of what role these discoveries or inventions played in the contemporary context of knowledge and how they changed their meaning when transmitted to a different context.

To address such historical-epistemological issues, an understanding is required of how reasoning operates in frameworks of knowledge that are not mathematized or otherwise structured as a deductive system and that differ even in their conceptual structure from later science. To account for an important aspect of such types of reasoning, I have in my own work made use of concepts of cognitive science to describe internal, i.e. mental, knowledge representation structures.[4]

Cognitive science has indeed offered some promising tools to the history of knowledge. It is true, however, that these tools are usually not applied to an understanding of the architecture of shared knowledge. Researchers in this field are interested primarily in acts of individual cognition, and how certain cognitive structures are identified and retrieved from memory during these acts. But for a theory of the evolution of knowledge, such structures are part of a transmitted macrostructure of knowledge. They are interesting mainly because they belong to a societal, that is, shared reservoir of knowledge from which an individual draws knowledge are also contributes to it.

In order to realistically capture historical thinking processes, it has turned out to be useful to employ concepts such as ‘frames’ or ‘mental models.’[5] Mental models are a particular form of knowledge representation that is especially suited for describing how conclusions are drawn from incomplete information. Often the missing information is supplied by prior experience. The concept of a ‘mental model’ as we have adapted it to the use in historical reconstructions is connected with the concept of a ‘model’ as a corresponding external knowledge representation structure. Below I will return in more detail to the role of such external representations. A material model, for instance a globe as a representation of the earth, supports the use of the corresponding mental model, the idea of a spherical earth, but usually cannot substitute it.

Knowledge representation structures such as frames or mental models can be understood in the context of non-monotonic logic.[6] Non-monotonic reasoning countenances the correction of inferences without having to change either the initial assumptions or the rules of inference. For a correction in non-monotonic logic, the premises of an inference are not negated but supplemented. This is what distinguishes it from classical logic. In the latter an expression that can be deduced from a set of premises cannot lose its validity when further premises are added. This is called the 'monotonicity' of classical logic, because additional premises may enlarge but not diminish the spectrum of inferences. However, human reasoning is typically non-monotonic: we often draw conclusions that we abandon in the light of additional information.

Non-monotonic logic is also suitable for understanding how scientific knowledge is dependent on experience and subject to correction. With its help it is possible to replace common anachronistic judgements of truth and falsehood in the history of science with a more appropriate picture of development and transformation of knowledge. The image is no longer one of linear cumulative development. Mental models, for instance, can be adapted to new experiences. With them we can understand changes in conclusions as resulting from changes in experiential context. Mental models connect present and past experiences by embedding new experience into a cognitive network that resulted from past experiences. And finally mental models form a connecting link between different forms of knowledge -- from practical to theoretical. With them it is possible, in particular, to treat the implicit reasoning processes inherent in the activity of practitioners, processes which may never be written down nor explicitly stated – a crucial premise for a history of knowledge.

Knowledge is not, however, just a mental structure. It also involves material and social dimensions that play a crucial role in determining what actions are possible and legitimate in a given historical situation. Knowledge may be shared within a group or a society. Material artifacts and external representations, such as instruments or texts, may be used in learning processes organized by societal institutions. In this way, individuals can appropriate the shared knowledge. The social and material dimensions of knowledge are hence critical for understanding its transmission from generation to generation.

One essential condition is given by the institutions governing the production, dissemination and appropriation of knowledge, which we shall designate 'the knowledge economy of a society'. More generally, institutions represent the potential of a society or a group to coordinate the actions of individuals interacting with their environment. As an 'action potential' these institutions are closely related to knowledge as we have defined it, but there are important differences. While there is no knowledge without the mental anticipation of actions, institutions must largely regulate cooperative behavior without such direct mental anticipation of collective actions and their consequences.

Actions are always embedded in and are part of a larger network involving other actors and the environment. The actors are assumed to have an internal, cognitive structure which governs the coordination of their actions and which in turn can change as a result of a reflection on their actions. The larger network also includes a given material and social culture that is the result of prior actions. In biological terms, this material and social culture corresponds to a niche that has been constructed by a species transforming its environment in such a way as to affect its own living conditions.[7] The material means are that part of the context employed by the actors to reach the goal of an action. They comprise, in particular, the tools available to a given culture and the useful material resources found in the environment. A crucial principle is that the material means constrain the range of actions that are possible in a given historical situation, thus defining a horizon of possibilities for actions (Damerow, 1996).

All contexts of action may furthermore serve as an external representation of the two key regulative structures we have been considering: knowledge and institutions. Such external representations can be used to share and transmit knowledge or to implement institutional regulations, but also to transform these regulative structures. I have already emphasized that external representations such as artifacts, tools and texts play a key role in the societal transmission of knowledge.

We thus recognize two essential, complementary features of a new model of cultural evolution:[8] the role of complex regulative structures, such as knowledge and institutions, and that of niche construction, such as the creation and transmission of a material culture that includes the external representations and the material means employed by these regulative structures. The crucial point now for understanding the evolutionary dynamics of this system is the fact that this niche construction not only depends on complex regulative structures, but also in turn shapes them. In other words, the material culture itself becomes a crucial factor in the evolution of institutions and knowledge. Rather than further explaining this dynamics in abstract terms, we will now look at some important turning points in the history of knowledge to illustrate how this framework makes it possible to explain the interaction between intrinsic and extrinsic factors in the process of cultural evolution.

4. The Emergence of Language

My first example will be a much-discussed subject, the origin of language, and here I rely on the work of Stephen Levinson and collaborators, in particular Judith Holler and Dan Dediu (Dediu and Levinson, 2013; Levinson and Holler, 2014). The acquisition of language in individual development clearly relies on biological and cultural factors. It should therefore be a good example for our framework because this framework is general enough not to force upon us a premature distinction between biological and cultural evolution. While the evolutionary mechanism giving rise to specifically human ways of thinking is often described in terms of distinct thresholds involving ecological circumstances driving humans into more cooperative ways of life and fostering adaptations for dealing with problems of social coordination (cf. Tomasello, 2014), this framework rather suggests a continuously working feedback mechanism in which these circumstances are themselves partly created by the regulative structures of human evolution through niche construction.

Human language is not without precursors in the animal kingdom. But it is unique in its generic capacity to communicate the coordination of actions independently from a situation involving these actions, thus allowing the accumulation and sharing of past experiences and the planning of future actions. Human language is also, as Levinson and his collaborators have recently emphasized, part of a multi-modal system of communication, involving vocalizations, but also body language, facial expressions, pointing, as well as contextual information stored in the environment. How did this unique human capacity result from an evolutionary process involving biological as well as cultural aspects?

The process must have started from a contingent ecological context constituting an external scaffold for initially fragile social interactions among our hominid ancestors.[9] Our framework now suggests a continuously working feedback mechanism in which the ecological circumstances acting as evolutionary driving forces are themselves partly created by the regulative structures of human evolution through niche construction. The material character of human actions therefore plays a crucial role, not only in their instrumental but also their representational aspects, which shape the transmission and transformation of the evolving regulative structures.

Even before the first proto-linguistic communication systems came into being, there must have existed some regulative patterns of cooperation such as *ad hoc* situative action coordination mediated by visual and other clues. Since the time of *homo habilis*, more than 3 million years ago, these regulative structures have been shaped by a shared material culture of tool use and transmission. Early communication systems, including gestures, pointing or facial expressions, would have initially only marginally supported such regulative structures, emerging as sporadic, domain-specific and highly context-dependent communicative interactions complementing other regulative structures and inheriting their 'meaning' from these structures.

Such rudimentary communication systems affect the development of cognitive capabilities by opening up an explorative space. This space exists precisely because communication systems constitute, just as the underlying material culture, external representations of regulative structures that typically have a larger horizon of applicability than that given by their initial purpose or circumstances of application.[10]

The gradual exploration and extension of this space enabled the discovery of new possibilities such as the ritualization and conventionalization of gestures. What may have been initially sporadic, situation-dependent signals within an originally only marginal communication process became eventually transformed into elements of a more and more self-sustaining system of communication, comprising, for instance, conventionalized gestures that are used outside of immediate action contexts. They now received their meaning not only from the contexts of action, but also from their role in the emerging communicative system.

This extension of the communication system enriched in turn the possibilities of action coordination and contributed to a stabilization of the actors' network by rendering it increasingly independent of the specific contexts in which it had emerged. Once a new communicative environment was established on the population level, the process could start again on an extended basis, eventually giving rise to a subsequent developmental layer. This opened up the possibility for an iterative process of language evolution eventually resulting in the layered, multi-modal structure of the human communication system that we actually observe today.

While the evolution of language is a case of biological-cultural co-evolution, this layered structure is something characteristic for knowledge in general. In my final example I will come back to the relevance of this observation for science, which, in fact, constitutes one such layer in a complex architecture of knowledge.

5. *The Neolithic Revolution*

My next example is almost of equal importance to the history of humanity as the evolution of language. Indeed, the transition from foraging or hunter-gatherer stages to food production is a major transition in the evolution of human societies that has hardly ever been considered in the context of a history of knowledge.[11] But food production involves not only new forms of interaction with the environment but also a different social and cognitive organization. The ultimate outcome of this transition could not have been anticipated at the beginning of the process. This raises the question as to which mechanisms drove human societies to change their subsistence strategies with such unpredictable consequences?

Developed agriculture is a comprehensive subsistence strategy involving intensive human labor. It represents an economic system by which human societies produce a large part of their food and other conveniences from domesticated plants and animals. Domesticated plants such as cereals are adapted to human nutritional needs and even rely on human intervention for their reproduction. In the evolution of food production the niche constructed by human interventions in the natural environment clearly played an important role; it was this niche that constituted the selective pressure for the biological transformation of the plants and animals involved. It also shaped the corresponding transformation of human societies, but not only in terms of changing selective pressures on these societies. Referring to the work of Bruce Smith, Melinda Zeder, Dorian Fuller and others, I would rather like to suggest that environmental changes were also part of an extended regulatory system that was eventually internalized in terms of social and cognitive structures to constitute a new economic regime no longer bound to specific local contexts but highly moveable with the societies that adopted it.[12]

Long before humans began to sow harvested seeds, they practiced various forms of landscape management, cultivating, for instance, wild cereals and pulses by tilling the soil. Unlike fully developed agriculture, predomestication cultivation in the sense of the manipulation of wild plants and animals did not constitute in itself a complete subsistence strategy, but only one component of such a strategy that was highly context-dependent. It evidently existed for a very long time in human history – playing, however, only a more or less marginal role for food production. Nevertheless, the means accumulated in this context, involving specific animals and plants as well as tools, showed under appropriate circumstances that they harbored an action potential exceeding the horizon of predomestication cultivation.

One context that evidently triggered a further exploration of these means was, at least in the Fertile Crescent, sedentariness. The first stable sedentary communities that appeared in the Early Natufian period in the Southern Levant, beginning around 14,600 years before our period, dealt with the challenge to appropriate a diverse set of natural resources, among them wild cereals, legumes, nuts and fruits. The early settlements were apparently even chosen so as to optimally straddle a variety of resources. Sedentariness favored the extension of cultivation practices bound to local environments. Given the investment of labor in cultivation practices, these in turn stabilized sedentariness thus creating what has been called ‘labor traps’ (Fuller, Allaby and Stevens, 2010). We thus see how the niche constituted by predomestication cultivation under the conditions of sedentariness could act as part of a regulative system channeling human actions along trajectories eventually leading to domestication.

Plants and animals adapted to a new cultural regime, constituting for them a niche that had not been created in order to produce this adaptation. Since cultivation was part of a network activity that was taking place in an extended geographical area (and not just in a small core region as has traditionally been assumed), migration and exchange among different sedentary communities eventually contributed to a diversification and enrichment of cultivars at any specific location. The resulting recontextualization of cultivation may have also helped to separate wild from cultivated populations. Eventually the domesticated crops and animals were no longer bound to the local contexts in which their ancestors were originally found but spread into other areas and ultimately across the world.

The ‘export’ of this model by carrying seeds and animals into new regions had a further recontextualization effect by contributing to its completion and recognition as an autonomous economic system. Eventually the expansion and transformation of settlement areas, population growth, as well as further structural changes of societies turned the Neolithic Revolution into a practically irreversible process of global extent.

This seems to be a general observation: globalization processes may lead to stability and even to irreversibility. It would be interesting to study what this means for science and science-based industrialization today, in the age of the Anthropocene. It seems the survival of humanity has become ever more dependent on these structures.[13]

6. *The Invention of Writing*

My third example, based on the work of Peter Damerow, Robert Englund and other colleagues, concerns the invention of writing in the late fourth millennium BC in the context of early urbanization and state formation in the sequel of the Neolithic Revolution.[14] In recapitulating this history we will again encounter some of the remarkable features highlighted by our framework of extended cultural evolution in the previous two examples, in particular, the transformation of external conditions into intrinsic features of the regulative structures, thus accounting for a growing 'universality' of these structures that remains, however, highly path-dependent.

As mentioned in the introduction, human societies involve a knowledge economy determining how knowledge is acquired, shared among individuals and transmitted across generations. One major transition in the history of knowledge economies is indeed the invention of writing as a symbolic representation of human language, making it possible to preserve, share and transmit knowledge coded by human language without involving direct personal interaction. The use of symbol systems goes back to at the least the Upper Paleolithic. But symbol systems were not invented for the specific purpose of representing human language. So, how did this specific use emerge and which kind of cultural evolution can account for this achievement?

A part of the answer lies again in the fundamental property of the material means of action and of the external representations of knowledge that the horizon of possible applications associated with them is larger than the goals pursued by any given set of actors. In the case of the emergence of writing in Mesopotamia in the second half of the fourth millennium BC, the process by which earlier symbolic systems were transformed into writing is well documented. One starting point was the modest accounting techniques that had been developed earlier in the context of a rural economy. The further development of these techniques was triggered by the emergence of large city states and their challenging demands on accounting techniques. Urbanization thus played a similar role for the exploration of symbolic culture, as sedentariness had played several millennia earlier for the extension of the cultivation of plants and animals.

Among the traditional accounting techniques were small clay tokens of different shapes serving as symbolic representations of objects and used for representing and controlling their quantities, but also seals representing certain administrative acts. The exploration of these given means, serving as external representations of administrative knowledge in the context of an expanding economy, eventually led to a transformation of the traditional symbolic culture. The exploration of the potential of the clay tokens stimulated, for instance, a proliferation of the number and shapes of these counters, which originally had been used only in small quantities in the context of the rural communities. The potential of existing tools of symbolic representation was thus exploited to its limits, with the effect of stabilizing the economy of the emerging city-states and of triggering reflections on the emerging cultural niche comprising these symbolic representations.

The symbols of the early Mesopotamian representation systems were highly context-dependent. The meaning they carried depended on the specific applications within the Babylonian administration for which they had been developed. But the potential of the early proto-writing to represent mental constructions reached far beyond this limited field of application. In its most developed form, reached after about a thousand years of exploration, it eventually included the possibility of representing spoken language and not just context-dependent forms of action coordination. Writing in the modern sense thus emerged from a representational system that was originally developed without this goal in mind. Such novel possibilities typically occur only as a side effect of the mainstream applications. It is also characteristic that the role of these marginal applications as being constitutive of a new developmental stage is only realized once a new perspective is introduced, often triggered by a new external context. In the case of writing, one such context was education (Nissen, 2011). Indeed, the growing complexity of the proto-writing system required institutional support for its transmission from generation to generation. But schooling implies a separation of the cognitive means of administration from their immediate context of application and thus opens up a perspective in which the potential of these cognitive means could be explored independently from the constraints of their application to solve concrete administrative problems.

The role of education therefore provides a good example of the emancipation of a system of knowledge from its embedding within concrete contexts of application. But there were other factors that may have similarly acted towards a recontextualization of the existing system of proto-writing, such as the spread of the system across cultural boundaries, consequently introducing a more reflective perspective on this system and enabling its repurposing to represent language. Just like the Neolithic Revolution, the invention of writing was therefore also a history of the ever-wider spread, of the 'globalization' of knowledge and of the increasing density of links within an expanding network of interactions.

7. The Evolution of Knowledge as Backbone to the History of Science

The title of this paper is 'from the history of science to the history of knowledge – and back'. Let me now come to the 'back'. How does this widening of perspective to include non-scientific knowledge help the history of science? My last example deals with the history of mechanics and the origin of the law of the lever. This has been studied jointly with Sonja Brentjes, Jochen Büttner, Peter Damerow, Peter McLaughlin, Matthias Schemmel and Matteo Valleriani.[15] The law of the lever is a theoretical statement about the inverse proportionality between weights and distances in a lever in equilibrium. The first documented formulation of such an inverse proportionality is found in the *Mechanical Problems* written, in part at least, as early as 330 BC and passed down as authentically Aristotelian (McLaughlin and Renn, 2015). From a modern perspective, the law underlies several mechanical devices that were used long before the *Mechanical Problems* were written. It is clearly relevant, even in its quantitative consequences, to understand the functioning of balances with unequal arms in which distances compensate changes of weight.

What is the relation between the theoretical formulation of the law of the lever and the knowledge underlying the invention, the production and the use of these mechanical devices? Without a more concise account of this knowledge and its genesis, it is impossible to answer the chicken-and-egg question of what was found first, the law of the lever or the balance with unequal arms? That this is a real chicken-and-egg question is suggested by the fact that balances with unequal arms were introduced in Greece not long before the first appearance of the law of the lever in writing. The earliest evidence of the introduction of balances with unequal arms comes from a play by Aristophanes, *The Peace*, which was first staged in Athens in 421 (Damerow, Renn and Rieger, 2002; McLaughlin and Renn, 2015). Aristophanes describes a so-called bismar. In a bismar, equilibrium is produced by altering the position of the fulcrum with respect to the beam, i.e., by varying the distances at which the weight as well and the load act. What knowledge was required to invent a bismar?

Answering the question of the relation between practical and theoretical knowledge makes it necessary to go back deeper in time to the origin of the concept of weight itself. Weighing technology was originally introduced for regulating social and cognitive processes dealing with the exchange of goods. In Mesopotamia weights used as exchange standards have been preserved at least since the Ur-III period, that is, since the late third millennium BC. The concept of weight results from reflection on operations with a balance. It has precursors in intuitive thinking about heavy bodies but emerged as a distinctive concept only when the balances with equal arms were invented, giving rise to a mental model of equilibrium.

The role of weight standards dramatically increased in the context of the political and economic globalization processes of the first millennium BC (Renn, 2014b). By the middle of the millennium, weight standards were widely spread in the Mediterranean world and beyond, along with the spread of coin money. This corresponds to the creation of a cultural niche in which a balance was no longer needed to establish equilibrium between two arbitrary weights. Rather, it could also serve to determine the relation between a given weight to a known standard. Neither the concept nor a standard of weight as such needed to be invented anymore but could simply be taken for granted. This now made it possible to pick up any instrument sensitive to weight differences such as a lever and to gauge it by means of some standard weight.

Remarkably, early testimonies of unequal armed balances, including the ones described by Aristophanes and a bismar found in Pompeii, are improvised from household objects: in the case of Aristophanes from a trumpet, in the Pompeian case from a pot (Damerow et al., 2002). The more familiar and widespread Roman steelyards are instead much more sophisticated instruments. So much for the knowledge required for inventing a balance with unequal arms. It very much relied on the cultural niche created by the prior invention of the balance with equal arms and the spread of its use, together with the relevant social and cognitive regulative structures.

What about the knowledge that could be gained from using and exploring such a balance with unequal arms? A reflection on operations with such balances gives rise to an extension of the equilibrium model because weight differences can evidently be compensated by differences of distances. But unlike the case of the lever, which is just used to 'save' force, in a balance with unequal arms this compensation between weight and distance must take place under the constraint of maintaining equilibrium. A balance with unequal arms is, at the same time, both a lever and a balance, so that two different mental models can be applied to it, yielding an integrated balance-lever model of practical knowledge that enables a qualitative understanding of the compensation process that takes place in such a balance (Renn and Damerow, 2007).

A subsequent step in the cultural evolution of the concept of weight occurred with the advent of written language. This new level of external representation allowed mental models of intuitive and practical knowledge to be externalized. The step was not taken because of an intrinsic logic in the development of weighing but for reasons completely external to it. The specific context of Greek culture gave rise to a tradition of philosophical writings dealing with natural processes and the astonishing power of human devices such as the lever to save force.[16] This seemed to contrast with the expectation that causes always correspond to their effects and are proportional to them, also rooted in intuitive and practical knowledge. But whereas such inconsistencies do not matter in intuitive and practical knowledge, they surface in the context of theoretical reflection on the knowledge structured by these models.

Accordingly, the seeming paradox that with the help of "tricky" devices, in Greek '*mechanai*', small forces can accomplish large effects became the starting question of the Aristotelian *Mechanical Problems*, the earliest text dealing with mechanics that has been preserved. The answer to the paradox is provided by showing that in these devices the same compensation mechanism is at work that characterizes the balance with unequal arms whose invention had given rise to the balance-lever model in the first place. The compensation mechanism is, in this philosophical context, not yet described in the familiar form of the law of the lever but as following from the 'miraculous' properties of the circle. But its qualitative formulation evidently came so close to the law of the lever that it was possible for a later editor to just read it into the text and amend it accordingly. The text thus functioned as a scaffolding for reinterpreting the compensation principle as the law of the lever. In the writings of later authors such as Archimedes, this novel insight could be tied to yet another level of external representation, that of Greek mathematics, in particular the theory of proportions, so that the law of the lever could now be quantitatively formulated and with it the foundation of a mathematical theory of mechanics.

This example shows how new 'challenging objects' such as the balance with unequal arms or other mechanical devices may enter the horizon of a theory like Aristotelian natural philosophy, triggering its further exploration, and eventually a reorganization of relevant parts.[17] In this way, core concepts and mental models are being enriched with new experiences and related to each other or to previously unrelated concepts.

The core regulative structures of the system of knowledge – in our example the core concepts of Aristotelian physics – will continue to organize such an extended system of knowledge, unless new regulatory structures, such as the law of the lever, emerge from the expanding niche through reflective abstraction. They may then become the starting point for a new, differently structured system of knowledge, which in our case is represented by the tradition of mechanics. As I have already indicated in the case of writing, the points of departure for the emergence of such new regulatory structures are typically those parts of the extended system of knowledge that are far removed from the core area and that are themselves well enough organized to act as nuclei and scaffolding for a reorganization of the system. In fact, the theme of mechanical devices is so far removed from the core of Aristotelian physics that many commentators have even doubted the authenticity of the *Mechanical Problems*.[18]

This example not only illustrates how closely the evolution of scientific knowledge is intertwined with the evolution of knowledge in general. It also suggests how one of the great riddles of the history of science may be resolved. The development of science is now recognized as being inextricably tied to other societal developments, shaped both by the local and global conditions of these developments. It nevertheless remains true that some concepts and mental models such as the concepts of number or of weight or the mental models describing the relation between force and motion play a key role in structuring scientific knowledge over vast periods of time. How can the persistency of these concepts, as well as their transformations over long periods of time, be explained?

Scientific theories are symbolic representations of complex knowledge architectures, of 'systems of knowledge', involving not just scientific but also other forms of knowledge.[19] Historically, the earliest examples of such organizing cognitive structures are rooted in intuitive and practical knowledge as we have just seen in the example of mechanics. In spite of their origins in deep history, the corresponding cognitive structures continue to this day to shape our experiences. On the one hand, this is due to the extraordinary flexibility of cognitive structures such as mental models, which allow details of the architecture of knowledge to be changed without abandoning its basic set-up. The longevity of some of these mental models, on the other hand, is due to the layered structure of this architecture of knowledge that I have earlier emphasized, and in which subsequent layers often do not substitute preceding ones, but incorporate them in a modified form as a part of a scaffolding. Thus, even the most abstract notions of weight in modern physics can still be related to the operations with a balance from which they originally emerged.

Contrary to what philosophers have long believed, the seeming universality of certain concepts is thus not the characteristic feature of a specific form of rationality. It is rather the outcome of a specific historical trajectory in the evolution of knowledge. If we want to understand how human experiences of the past have shaped today's science and how we may shape it in the future we have to understand these trajectories.

Acknowledgements

This is an edited version of a talk given in Lisbon on the occasion of receiving the Neuenschwander Prize 2014. I am deeply grateful to the European History of Science Society, to its selection committee, to its president Fabio Bevilaqua, and to the generous sponsor, Erwin Neuenschwander. I am grateful also to Ida Stamhuis for her encouragement and support in transforming my Lisbon talk into this contribution for *Centaurus*. Lindy Divarci has been of invaluable help, as so often, with her careful editing of the manuscript. Manfred D. Laubichler has played a crucial role in developing the idea of extended evolution. My heartfelt thanks also go to all my colleagues from the Max Planck Institute for the History of Science for their collaboration and, in particular, to Matthias Schemmel and Matteo Valleriani for the intensive discussions in preparing this paper.

NOTES

1. For an overview, see Renn 2012, on which much of the following is based; see also Renn, 2014c.
2. For an introduction to the theme of the Anthropocene and its implications for cultural history, see Klingan, et al., 2014.
3. The framework owes much to Elkana, 1981, 1986; Damerow, 1996.
4. See, e.g., Renn and Damerow, 2007; Renn and Sauer, 2007.
5. See, e.g., Minsky, 1975; Gentner, 1983; Minsky, 1988.
6. See, e.g., Reiter, 1978, 1980; McDermott and Doyle, 1980; Moore, 1985; Antonelli, 2006.
7. Niche construction is a prominent theme in current discussions of evolutionary biology and cultural evolution, see Laland et al., 2000; Odling-Smee et al., 2013; Richerson and Christiansen, 2013.
8. The idea of an extended evolution integrating regulatory networks and niche construction has been developed jointly with Manfred D. Laubichler.
9. On the notion of scaffolding, see Wimsatt, 2013; Caporael et al., 2014.
10. This space corresponds to Vygotsky's zone of proximal development, see Vygotsky, 1978. For its use in an explanation of the emergence of language, see Damerow, 2000. See also Lock, 2000.
11. For a sketch of such an attempt, on which the following is also based, see Renn, 2014a.
12. Smith, 2007; Zeder, 2009; Asouti, 2010 and Fuller et al., 2010.
13. See Haff, 2013; Smith and Zeder, 2013. See also Survey 4 in Renn, 2012, pp. 561–604.
14. The following is based on Nissen et al., 1993; Damerow, 2012. See also Renn, 2014a.
15. See Renn and Schemmel, 2000; Damerow et al., 2002; Renn and Damerow, 2007, 2012; Valleriani, 2009; Brentjes and Renn, 2015; Büttner and Renn, 2015; McLaughlin and Renn, 2015.
16. For a comparison with the Chinese situation, see Renn and Schemmel, 2006.
17. The concept of challenging objects has been introduced in Renn et al., 2001. For later developments, see e.g., Büttner, 2008.
18. See the discussion in Krafft, 1970; see also McLaughlin and Renn, 2015.
19. For the concept of knowledge systems, see Damerow and Lefèvre, 1998.

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