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The Early History of Weighing Technology from the Perspective of a Theory of Innovation

The article advances a framework allowing for a unified description of technical innovation and the advancement of theoretical knowledge. Cognitive structures based on foregoing actions with physical objects are externally represented by artifacts, language or writing. The exploration of actions with these external representations such as the fabrication and usage of new devices or the composition of texts opens up new possibilities for a reflective abstraction leading to new cognitive structures. The exploration of the options for actions is canalized by historically specific contexts constraining the actors. Based on the example of the early history of weighing with a focus on the establishment and differentiation of unequal-arm balances we elaborate the consequences of such an account.

Evolution of knowledge; mechanics; weighing technology; innovation; practical knowledge; unequal-arm balance.

1 The origin of weighing technology and its conceptual consequences

The technology of weighing emerged when administrative and economic developments of early urban societies began to involve standards for exchange values. In Mesopotamia standardised weights used for this purpose have been preserved since the ED IIIa (Fara) period (mid-third millennium BC).[1] In the context of the political and economic globalization processes of the first millennium BC the role played by these crucial standards even increased.[2] By the middle of the first millennium coined money was widespread in Lydia, Greece and India, and somewhat later also in China. In Egypt and probably slightly later in Mesopotamia the lever balance with equal arms of fixed length was introduced at around the turn from the fourth to the third millennium. Balances evolved as well, but their basic principle remained the same for millennia: the weight of the item to be weighed on one arm of the balance was compensated (or literally 'balanced') by the identical weight of one or more standardized balance weights placed on the other arm of equal length. This only changed when a new type of balance obeying a different principle emerged: the balance with variable arm length, more commonly referred to as the unequal-arm balance. This type of balance is recorded in the late fifth century BC in Greece and may have been in use at the same time or somewhat later in India.[3] The spread and transformation of weighing technology was thus closely associated with economic evolution.

These economic and technological developments went hand-in-hand with conceptual transformations. The introduction of standards for exchange values together with an emerging practice of weighing gave rise to an abstract and quantitative concept of weight, distinguished from other bodily characteristics such as bulk or material quality. The spread of the unequal-arm balance led to a further differentiation of this concept, also taking the

1 See Sommer 2013, chap. 6. See also the contribution of Topoi research group D-6 in this volume.
2 See Geller 2014.
3 See Renn and Dahlem Workshop on Globalization of Knowledge and its Consequences 2012.

positional effect of a weight into account. In the course of the globalization processes of the first millennium writing was simplified and spread. In particular alphabetic writing was fully developed and various literary cultures formed in different parts of Western Eurasia and Northern Africa.[4] In Greek culture, characterized by its marginality to some of the major contemporary empires, its widespread connectivity and exchange with other cultures, plus the emergence of discursive practices beyond political and religious realms, these globalization processes formed the backdrop for the creation of a scientific literature in which the new abstract concepts were taken up and further developed.[5] The first Greek texts dealing with "mechanics" focused in one way or the other on the properties of the balance and the concepts that had been abstracted from weighing technology. These concepts, rooted in globalized economic and technological developments, thus became part of a long-lasting literary tradition that persists in science even today.[6]

Various technological traditions evolved parallel to the emergence, transmission and transformation of this literary tradition. In the Mediterranean region during the period under consideration here, machines were circulating in increasing quantities; if not the actual machines, then at least the operative knowledge of how to build, use, maintain and repair them. Engineers and mechanics were rarely able to remain in the place where they accomplished a technological feat, and were obliged to travel to wherever a new machine was required. Thus, the need to communicate and disseminate the know-how associated with the new technology also emerged. It was technology, therefore, that represented the primary vehicle for the transfer of mechanical knowledge. Technologies both changed over time and differentiated regionally, and such changes were not limited to the optimisation of function. Indeed, a broad range of factors can be identified that triggered or even necessitated changes in certain technologies, such as the availability of new raw materials, new methods of fabrication or the widening of the range of application of a given technology.

The factors regulating the diffusion and development of the knowledge underlying the production, adaptation and use of technology are different from those governing the transmission and development of theoretical knowledge predominantly encoded in texts. For a very long time, the innovation and diffusion processes of these textual and technological traditions followed different pathways. This was due to the knowledge economies generating technological and intellectual novelties not being closely coupled until early modern times, when technical artefacts became objects that challenged theoretical traditions.[7]

Nevertheless, the transmission of theoretical texts on mechanics could not be independent from the transmission of a material culture constituting key points of reference for concepts contained in these texts and inducing, at several junctures, important theoretical insights. Thus, it is hardly conceivable that the science of weights in the Arabic and Latin Middle Ages could have flourished without the material basis of widespread weighing practices. Intellectual novelties such as the elaboration of concise concepts for the positional qualities of weight depended, however, not only on technical developments, but also on changing discursive contexts such as for instance those offered by the appropriation of Greek texts by Islamicate and of Arabic texts by Latin scholars.[8] Technological innovations, on the other hand, such as the Roman steelyard, could hardly profit from

4 See "Survey 1" in Renn and Dahlem Workshop on Globalization of Knowledge and its Consequences 2012.
5 See Malkin 2013 [2011].
6 See Damerow and Renn 2010.
7 See Büttner 2008a; Büttner 2008b; Valleriani 2009; Valleriani 2010; Valleriani 2012; Valleriani, Divarci, and Siebold 2013; Valleriani 2014; Damerow and Renn 2010.
8 See Brentjes and Renn 2015.

theoretical knowledge that only dealt with fundamental principles such as the law of the lever but not with the intricacies of their material implementation. The extent to which genuinely theoretical insights nevertheless may have affected the course of the development of technology and technological knowledge in antiquity is still largely an open question.

2 The cultural evolution of practical and theoretical knowledge

In light of this – for the most part – independence of the technological and theoretical developments that interacted over a period of more than two millennia, the comparative study of the dynamics of the innovation characteristic of these two strands becomes relevant, as does posing questions about their commonalities and differences. So far the focus of studies has been primarily on the scientific, theoretical side, mostly neglecting the distinct innovation dynamics of technology.

Scientific innovations are often contingent on technological developments. The law of the lever for instance was formulated on the basis of theoretically motivated reflections on a technical device, the unequal-arm balance. However, the transmission and accumulation of scientific knowledge largely depends on texts such as the early mechanical writings of Greek culture. Given the limited feedback of scientific knowledge on the technological development itself, its textual transmission in turn depended on other historical contingencies than those relevant to the development and spread of technology and technological knowledge.

Until modern times, text transmission in literate societies focused on administrative, practical, legal and religious texts, as well as on other literary texts constituting cultural identity, while philosophical and scientific literature with its limited practical value constituted at best a secondary phenomenon. Nevertheless, the knowledge economy dealing with these esoteric matters participated in general societal processes of incorporating new experiences. Reflecting on its own production, science was able to generate new abstractions – cognitive as well as institutional.

This dynamic, familiar from studies of the evolution of theoretical knowledge,[9] warrants closer inspection in order to assess its relation to technological innovation. As we have mentioned, weighing technology had originally been introduced for regulating social and cognitive processes dealing with the exchange of goods. In weighing these regulative processes find "external representations".[10] These external representations comprised among others standard weights, the balance, and a specialized technical terminology. The reflection on these external representations gave rise to an abstract concept of weight, as part of a particular conception or mental model of equilibrium. This model turned out to be applicable not just to weights and weighing, but also to other abstract values such as justice.[11] In fact, the embedding of the concept of weight in a broader linguistic usage increasingly connected it with other concepts or suggested metaphorical generalizations. Thus the reflection on the external representations associated with weighing technology eventually led to a transformation and extension of social and cognitive structures, not all of which related directly to weighing.

Based on the concrete example of the balance with variable arm length, a brief explanation will now be given of how a more differentiated picture of the innovation dynamics of technology and the underlying technological knowledge can inform our general understanding of the relation between technology and science in antiquity.

9 See Damerow 1996.
10 See Integrating Regulatory Networks and Construction 2015.
11 See Renn and Dahlem Workshop on Globalization of Knowledge and its Consequences 2012.

3 Unequal-arm balances as a technical weighing innovation

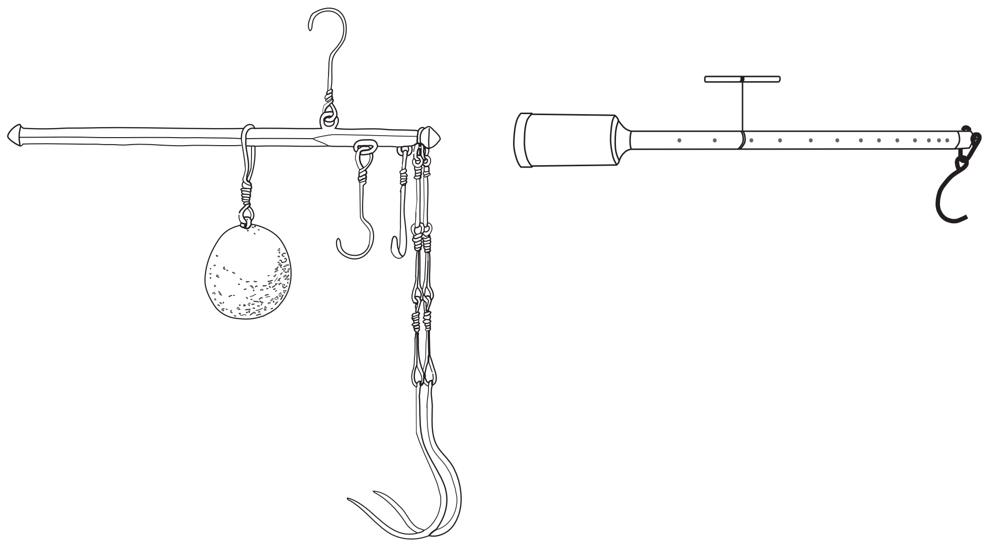


Fig. 1 | Schematic representation of the two different major types of balances with unequal arms, the Roman steelyard (left, subtype Osterburken; redrawn from Franken 1993) and the bismar or Danish balance (right).

Balances with variable arm length, or unequal-arm balances as they are more commonly referred to, belong to the more general class of lever balances, characterized by a rigid beam allowed to turn around a point of suspension: the fulcrum. Such balances are in equilibrium when the sum of the moments of force with respect to the fulcrum is zero, a general condition that, under certain constraints, coincides with the law of the lever. Depending on how equilibrium is established in such balances, one can distinguish balances with a fixed arm length from balances with variable arm length.[12] In the case of balances with fixed arm length, equilibrium is produced by putting on or taking away weights, i.e., by altering the acting forces. The most common realisation of this is the equal-arm balance, which, as mentioned before, was first introduced around 3000 BC. In balances with variable arm length, the counterweight remains unchanged. Instead, the distances at which the forces act from the fulcrum are varied to bring about equilibrium. Somewhat misleadingly, this type of balance has come to be referred to as the unequal-arm balance.

Unequal-arm balances can further be subdivided according to the way in which the relevant distances are varied. In the bismar, equilibrium is produced by altering the position of the fulcrum with respect to the beam, i.e., by varying the distance at which the weight as well as the distance at which the load acts. In the more familiar Roman balance,

12 An alteration of both the counteracting force and the length of the arms on which the forces act is conceivable and was in fact realized historically in form of the equal-arm balance with an additional counterpoise. A number of finds suggest that this type of balance, which was fairly common in the Roman imperial period, may be of earlier origin than the steelyard and the bismar types discussed in somewhat more detail in this article. The equal-arm balance with additional counterpoise has not yet received due attention in the literature. For an albeit cursory description, see Corti and Giordani 2001. At the current stage of research, we must assume that the steelyard evolved from this type of balance.

also referred to as the steelyard, equilibrium is reached by varying the distance at which a movable counter-weight acts from the fulcrum.[13]

The earliest evidence of the introduction of balances with variable arm length comes from a play by Aristophanes, *The Peace,* which was first staged in Athens in 421 BC. In the play, a maker of war trumpets is ridiculed because he cannot figure out what to do with his surplus trumpets. Trygaeus, the central character of the play, suggests pouring lead into the bell and to add “a dish hung on strings, and you will have a balance for weighing the figs”. Despite being rather abridged, this description of the transformation of a trumpet into a balance makes it rather unambiguously clear that the trumpet is turned into a specific unequal-arm balance, the bismar.[14]

4 The first writings on mechanics as a theoretical weighing innovation

A subsequent step in the cultural evolution of weighing technology occurred when some of the extended cognitive processes it entailed (such as the introduction of an abstract concept of weight or the realization that weights can be compensated by distances in the new balances with variable arm length) were externalized by a new level of external representation: the documentation in written language. This step was, of course, not taken because of an intrinsic logic in the development of weighing technologies, but for reasons completely external to it. In particular, 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 to modify their properties. The first documented example of a sustained theoretical reflection on mechanical knowledge is the peripatetic *Mechanical Problems,* written, in part at least, as early as 330 BC[15] and passed down as authentically Aristotelian. The knowledge presented in the *Mechanical Problems* was the point of departure for later, more advanced work in mechanics that informed the writings of Archimedes, Hero of Alexandria, or Vitruvius.[16]

The theoretical knowledge represented by these texts was structured by mental models such as the equilibrium model, a model of causality relating force and effect, or the lever model, according to which a lever can be used to save force. Such models were based on and encoded intuitive and practical physical experiences, among them the experiences gained in weighing. With the medium of writing it became possible to reflect on the application of these models and relate them to each other. Thus, the joint application of both the equilibrium and the lever model to balances with unequal arms led to a new mental model, the balance-lever model. This balance-lever model provided the means to interpret various force-saving mechanical devices as working due to a compensation relationship between force and lever arm: a precursor of the law of the lever. This allowed an explanation of the apparent conflict between their force-saving power and the proportionality of force and effect suggested by the causality model.

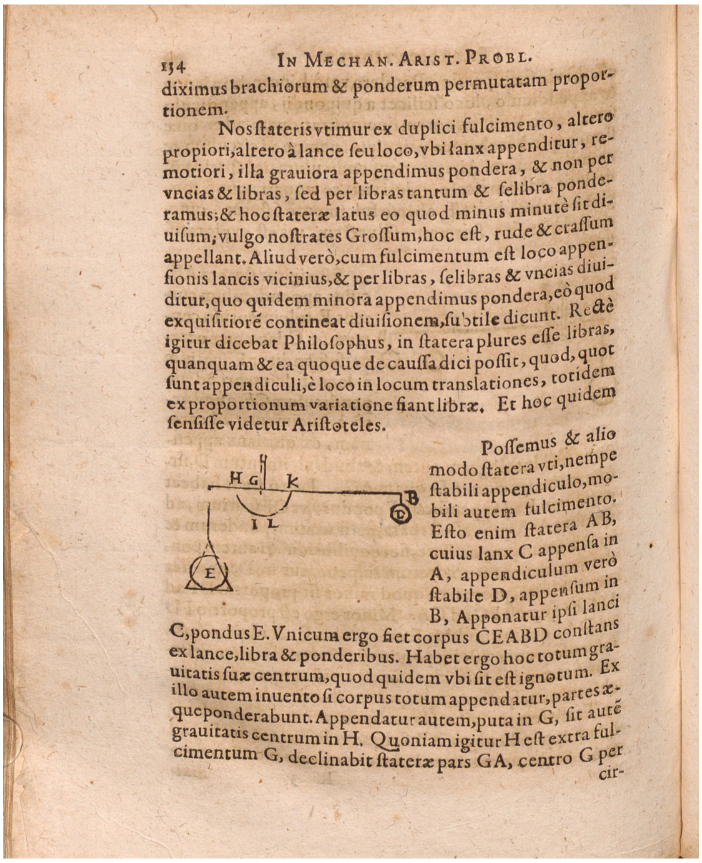
Similarly, the reflection on the application of the equilibrium model not just to balances, but also to other devices led to a further abstraction of this model by generalizing the fulcrum of a balance to the notion of a centre of gravity in principle applicable to

13 The third perceivable variation, a balance in which the distance at which the load acts is altered to achieve equilibrium, was occasionally realized historically but never really established. See Jenemann 1989.

14 See Büttner 2013.

15 The work is presumably pre-Euclidean and may have been initiated during Aristotle’s lifetime. Euclid’s *Elements* are generally taken to have been compiled shortly after 300 BC; Aristotle died in 322 BC. See McLaughlin and Renn (forthcoming).

16 Vitruvius’ work on mechanics is contained in chapter X of his *De Architectura* (Pollio 1999). For a recent analysis of the *Mechanical Problems* see McLaughlin and Renn (forthcoming).



134 IN MECHAN. ARIST. PROBL.

diximus brachiorum & ponderum permutatam proportionem.

Nos ſtateris vtimur ex duplici fulcimento, altero propiori, altero à lance ſeu loco, vbi lanx appenditur, remotiori, illa grauiora appendimus pondera, & non per vncias & libras, ſed per libras tantum & ſelibra ponderamus; & hoc ſtateræ latus eo quod minus minutè ſit diuiſum; vulgo noſtrates Groſſum, hoc eſt, rude & craſſum appellant. Aliud verò, cum fulcimentum eſt loco appenſionis lancis vicinius, & per libras, ſelibras & vncias diuiditur, quo quidem minora appendimus pondera, eò quod exquiſitioré contineat diuiſionem, ſubtile dicunt. Rectè igitur dicebat Philoſophus, in ſtatera plures eſſe libras, quanquam & ea quoque de cauſſa dici poſſit, quod, quot ſunt appendiculi, è loco in locum translationes, totidem ex proportionum variatione fiant libræ. Et hoc quidem ſenſiſſe videtur Ariſtoteles.

Poſſemus & alio modo ſtatera vti, nempe ſtabili appendiculo, mobili autem fulcimento. Eſto enim ſtatera AB, cuius lanx C appenſa in A, appendiculum verò ſtabile D, appenſum in B, Apponatur ipſi lanci C, pondus E. Vnicum ergo fiet corpus CEABD conſtans ex lance, libra & ponderibus. Habet ergo hoc totum grauitatis ſuæ centrum, quod quidem vbi ſit eſt ignotum. Ex illo autem inuento ſi corpus totum appendatur, partes æqueponderabunt. Appendatur autem, puta in G, ſit autē grauitatis centrum in H. Quoniam igitur H eſt extra fulcimentum G, declinabit ſtateræ pars GA, centro G per cir-

Fig. 2 | Page from Bernardino Baldi's *In Mechanica Aristotelis problemata exercitationes: adiecta succinta narratione de autoris vita et scriptis* of 1621. Problem 20 of the *Mechanical Problems* refers to a bismar. Baldi, as many other 16th-century authors studying and discussing the work, however, believed the problem to pertain to the familiar Roman steelyard and thus had considerable problems in interpreting the problem (see Baldi, Nenci, and Carugo 2011).

arbitrary bodies. The concept of "centre of gravity" played a crucial role particularly in the work of Archimedes.[17] In his writings, these novel theoretical structures and their implications were represented with recourse to Greek mathematics, in particular the theory of proportions, so that the law of the lever could be quantitatively formulated. Thus, the foundation of a mathematical theory of mechanics was laid.[18]

To sum up, we recognize an iterative process in which cognitive structures based on foregoing actions with physical objects are externally represented by artefacts, language or writing and in which the exploration of actions with these external representations (such as the fabrication and usage of new devices or the composition of texts) opens up new possibilities for a reflective abstraction leading to new cognitive structures. In this iterative process, the exploration of the options for actions is canalized at each step by historically specific contexts constraining the actors. Being dependent on contingent boundary conditions, this process is highly path-dependent, i.e. present structures can depend on antecedent contexts that are no longer necessarily given. The contributing actors form a network of interactions that is regulated by their internal cognitive and external social structures. The cognitive structure is shaped by material culture and capable of change due to the same. More than merely providing a selective, independent context for the activities of the actors, material culture thus incorporates the external representations of the very structures that regulate the actor's actions.[19]

17 See Di Pasquale et al. 2013.
18 See Knorr 1982.
19 See Integrating Regulatory Networks and Construction 2015; See also the contribution of Jürgen Renn in the proceedings of the Topoi-Jahrestagung 2013, forthcoming.


Archimedis
Zwey Bücher
Von derer
Ebenen Flächen
Gleichwichtigkeit und
Schwäre-Puncten.

Die Haupt-Lehren
beyder Bücher.

Der XIV. Lehrsatz
des I. Buchs.
Der Punct wo 2 und 1 sich in dem Durchschnitt trennen/
Macht jedes Dreyeck recht/ und waaggleich inne stehn:

Der VIII. Lehrsatz
des II. Buchs.
Man soll den Schwäre-Punct in der Parabel nennen
Den/ wo 3 oben/ 2, von fünfen/ unten gehn.

Fig. 3 | Title page of Archimedes *On the Equilibrium of Planes* in a German translation of 1670 (*Des unvergleichlichen Archimedis Kunst-Bücher oder heutigs Tags befindliche Schriften*, translated and commented by Johann Christoph Sturm, Nürnberg). In this work Archimedes first introduced the concept of a center of gravity which can be understood as generalizing the notion of the fulcrum of a balance.

5 Technical innovation and the evolution of knowledge

Can this scheme be applied also to technological innovation processes? Technological devices are external representations of the institutional and cognitive regulative structures of the societies that invent, produce and use them, and they shape these structures in turn by creating spaces of action that determine what people can and cannot do with them under the given historical circumstances. In technological development we can furthermore distinguish features of the development of theoretical knowledge as described above. A given generation of technological devices acts as a precondition for the creation of the next generation where, as a rule, it is the exploration of the potential of the preceding generation that provides the means to enable the creation of novelty.

Subsequent layers of technology do not completely replace earlier ones, which, instead continue to act as scaffolding, albeit in a modified form. This is particularly true for the practical and technological knowledge associated with the devices, which in this respect compares to theoretical knowledge. In the realm of theoretical knowledge, we first have to learn for instance how to count before we can understand number theory. In the realm of technological knowledge, sophisticated balances with variable arm length for example rely on standard weights that in turn are a product of equal-arm balances.

An important difference between theoretical and technological knowledge, however, is the relationship between the external representation of the knowledge and the underlying cognitive and institutional structures. Theoretical knowledge can typically be appropriated by an individual through texts that are understandable with certain prior knowledge and under certain external circumstances; in particular the meaning of the main concepts used in a text have to be part of the shared knowledge of the group to which the individual belongs. The individual may also be required to have accumulated certain specific experiences prior to being able to understand a text. Practical and technological knowledge, in contrast, may not even pertain to an individual but may involve the distributive knowledge of a group cooperatively solving a technical problem – without any single individual intellectually mastering the entire process. A typical way for an individual to appropriate practical knowledge is by participating in joint working processes which involves joint attention, observing others, imitating them, taking on their perspectives, gaining and articulating experience with the same tools they are using, taking up hints and learning from corrections.

Practical knowledge is often characterized as 'implicit knowledge' because its verbal expression provides for only a very limited aspect of its transmission. Actually, however, such knowledge is characterized by typically requiring an even broader array of media and structured information for its communication than theoretical knowledge. Its external representation may comprise samples, a variety of tools, demonstration of their usage, verbal explanations (possibly involving technical terminology), drawings or models and a specific distribution of labour, as well as social and material contexts that may indeed not be made explicit but are taken for granted in a particular culture. This renders, as a rule, the transmission of practical and technological knowledge much more context-dependent than the communication of theoretical knowledge through texts, as is witnessed by the difficulties of reverse engineering. This context-dependency – and hence locality – of practical and technological knowledge, is often reinforced by the fact that technical solutions at least until the pre-modern period were themselves mostly tuned to specific contexts.

The dependence of technological knowledge on multiple forms of external representations, each connected with its own regulative structures also accounts for the stability of this kind of knowledge, at least as long as the relevant contexts for its transmission do not substantially change. If the relevant contexts for its transmission change on the other hand, technological knowledge is much more easily irrefutably lost than theoretical knowledge.[20] It is also much harder to reflect on and to successfully alter such a wide-ranging array of external representations than on the operations of a single device, or on symbolic representations of theoretical knowledge.

A general account of technical innovations along the lines sketched above suggests a number of distinctive features that should be identifiable in the early history of weighing technology: a superposition or co-existence of various stages, some serving as the scaffolding for others; a relative scarcity of innovations due to canalization; a crucial role of additional regulatory factors for the occurrence of larger innovations; and a transformation of the 'inheritance system' underlying the transmission of technology. The superposition of layers is a consequence of the iterative evolutionary process described above. The scarcity of innovations follows from the fact that, at each step, the space of evolutionary possibilities is circumscribed by the available means and external representations. The crucial role of additional regulatory factors follows from the fact that the effect of a variation is not random, but may be small or large according to its role in the context of regulatory structures. Major innovations are due to changes upstream in the regulatory apparatus. The transformations of inheritance patterns are a consequence of the fact that the boundaries of technological systems are not fixed.

20 In the history oft he steelyard this tendency is nicely illustrated by the apparent loss oft he ability to produce fully functional steelyards with two or three fulcra in the Merovingian period. See Werner 1954.

6 The co-existence of different lineages

The results of our investigations into the early history of weighing technology as they have been pursued so far are in agreement with the theoretical explanation of innovation sketched above.[21] In the history of weighing technology, various types of balances emerged, were widely spread and continue to coexist until today. This is evidently the case for the equal-arm balance and the Roman balance. It also applies, with some reservations, to the bismar. Aristophanes' passing allusion to the instrument suggests that his audience would have been familiar enough with it so as to understand the pun he makes in the play. In the *Mechanical Questions* it is stated that bismars were used to weigh meat. It thus seems that the bismar had been a rather common weighing instrument since at least the end of the fifth century BC. Such a conclusion, however, does not seem to be supported by the archaeological record. Whereas the absence of any artefacts from the early period could potentially be explained by the fact that, at least initially, bismars were made out of wood and would thus not have been preserved, the lack of pictorial representations suggests moreover that the bismar persisted next to weighing with equal-arm balances only as a somewhat marginalized technology.[22]

Yet, a second linage in the history of the bismar, can be discerned which has mostly been ignored. In India, bismars are attested as early as the end of the fourth century BC in writing as well as pictorially.[23] The archaeological record suggest that there the bismar enjoyed a continued tradition and can still be found in use today.[24] It is certainly possible that here we are concerned with independent developments. Yet, acknowledging the fact that balances had been in use in both cultural areas, the Aegean and the Indus valley, for more than 2000 years, the emergence of the very same modification of weighing technology at apparently more or less the same time must be taken as a strong indication that this is the result of a transfer of technology.[25] Further research is required to answer the question and, should this be the case, decide in which direction the transfer of technology actually took place.

7 Canalization and scaffolding: the case of the bismar

The mechanical lever balance constitutes a physical system with a limited design space for arranging load, fulcrum and standard weight.[26] Yet, even this limited design space has not been fully exploited, since the case of a moveable load has historically not played a notable role.[27] Given one of the basic "body plans" for balances, further innovations took the form of exploring the optimisation possibilities inherent in it. Larger innovations associated with changes in the body plan went along with the existence or introduction of new regulatory structures related to weighing, at most only indirectly.

The basic invention of the first balances with unequal arms (i.e. balances of the bismar type) thus presupposed the firm establishment of a weight system represented by sets of

21 The theoretical explanation presented here is informed by a theory of extended evolution as laid out in Integrating Regulatory Networks and Construction 2015.

22 As the abundant representations of weighing with equal-arm balances that have been preserved show, the lack of pictorial representations of bismars cannot be explained by the fact that weighing as an every-day technology was not the subject of such representations.

23 See Jenemann 1994. A bismar is mentioned in chapter XIX of the *Arthashastra,* an ancient Indian treatise on state governance. See Kautalya 1992.

24 See Dikshit 1957 and Dikshit 1961.

25 For the earliest evidence of weighing in the Indus valley culture see Kenoyer 2010.

26 For the concept of design space, in particular in relation to the formation of specific "body plans" or "dominat designs", see Murmann and Frenken 2006.

27 See Jenemann 1989.

Fig. 4 | Greco buddhist bas relief from the ancient region of Gandhara (today border region between Afghanistan and Pakistan) from the 2nd to the 3rd Century showing a scene from one of Buddhas former lives as king Sibi. In the center flesh cut from the kings leg is weighed with a balance which is obviously a bismar.

standard weights as the cognitive and social regulations needed to empirically gauge such a balance and make this gauging acceptable to its users, without requiring any further sophisticated knowledge. The bismar is indeed a rather simple instrument; palpably its most complicated feature is its non-linear scale where the scale intervals representing equal weight differences follow a harmonic division. It can confidently be stated, however, that in antiquity scales of bismars were not theoretically established but empirically constructed by gauging.[28] If this is taken into account, it becomes manifest that the construction of a bismar indeed only poses minimal requirements to the underlying mechanical knowledge. The law of the lever governs the operation of a bismar, just as that of many other instruments. The assumption that knowledge of the law would have been required to build a bismar is, however, as pointless as the assumption that it would be required to build a set of pliers.

The transformation of an everyday item such as trumpet into a bismar alluded to in Aristophanes' play underscores the comparatively little requirements posed by the construction of a bismar. One could, of course, dismiss the passage in Aristophanes as literary fiction, having little or no informative value concerning the actual feasibility of the transformation of an everyday item into a bismar were it not for a peculiar object found in Pompeii.[29] In the case of this object from Pompeii, an ordinary kitchen casserole (as hundreds of them were found in the Vesuvian town) has been transformed into a bismar. To this end the handle of the casserole was merely furnished with a slit, in which a suspension attachment could be linked, and a load attachment was adjoined to the handle thus bearing witness to the relative ease with which a bismar can be fabricated.[30]

The advantages of the simple construction of the bismar stand in contrast to a certain shortcoming in its application for weighing purposes. Since in a bismar the fulcrum can

28 A statistical analysis of the deviation of the scales' marks from their ideal positions in Roman steelyards has shown that the scales of these balances were produced by gauging at regular intervals. The intermediate marks were placed by dividing the distances into an appropriate number of equal parts. As concerns the bismar, a similar gauging routine for the establishment of the scales has been assumed (see Damerow, Renn, et al. 2002 and Jenemann 1994) but awaits confirmation by a detailed examination of the objects.

29 Aristophanes' description is, however, not merely based on a superficial similarity of a trumpet and a bismar, as the instruction to fill the bell with lead corresponding to construction knowledge illustrates.

30 A summary of the discussions of this particular object can be found in Damerow, Renn, et al. 2002. Jenemann (Jenemann 1994) takes the Pompeian bismar as an indication that bismar technology was still in widespread use in the second half of the first century. In view of the simplicity of the construction the argument is not very cogent.

move arbitrarily close to the load suspension, its weighing range is potentially infinite, limited only by the stability of the beam. However, in practice resolution and the accuracy of a bismar necessarily decrease with higher loads so that weighing becomes less expedient as small displacements of the fulcrum correspond to great differences in weight. A bismar is thus particularly suitable only for determining small weights. Small weights and weight differences are especially relevant when dealing with valuable goods where accuracy matters. Thus, precisely in the weight range where the bismar shows its specific strength, it is in direct competition to equal-arm balances which are potentially more accurate by design. This may provide an explanation why, as suggested above, the bismar was a somewhat marginalized technology compared to weighing with equal-arm balances, of which there is ample evidence in the relevant period.

8 Canalization and scaffolding: the case of the steelyard

We have emphasized that larger innovations associated with the change of "body plans" require the existence or introduction of new regulatory structures acting as scaffolding. In the case of the bismar we have seen that the pre-existing level of knowledge as well as of societal regulations involving the abstract concept of weight and its representation by a series of standard weights acted as such scaffolding, allowing a new type of balance to be improvised by empirically gauging its scale. As we will see, the introduction, spread and development of the steelyard placed much higher demands on the underlying structures.

The earliest evidence for the steelyard comes from a number of archeological finds that can be dated approximately to the middle of the first century BC. Vitruvius mentions the Roman balance a little later in his *De architectura*. Here, he refers to it as *statera* and explains its function by a qualitative law of the lever.[31] Only a handful of steelyards can be dated with certainty before the Common Era and, for this early period, the finds remain somewhat confined to the Roman core territory. From the middle of the first century CE onwards, however, a rapid growth in number of preserved artifacts is observable. Clearly, the steelyard became widely used and produced all over the Roman Empire.[32]

The Roman steelyards with two or even three fulcra were much more sophisticated than the bismar. Their introduction and spread required the articulation and transmission of sets of rules within an appropriate societal infrastructure. In contrast to the case of a bismar, the construction of such a steelyard cannot be achieved by improvisation; the mechanical knowledge required to successfully design and fabricate a steelyard is much more intricate. In order to manufacture a steelyard suitable for weighing purposes, a number of non-trivial boundary conditions have to be satisfied. Many, but far from all of, the problems that have to be solved in fabricating a steelyard are related to the dead weight of the instrument, i.e. that the instrument has a weight, which, opposed to the case of the equal arm balance, influences its equilibrium.[33] In a certain way the steelyard can be said to weigh itself. The problems encountered in successfully designing a steelyard shall be briefly indicated below based on two examples.

31 Peculiarly, Vitruvius' description is the only unambiguous reference to a steelyard that can be found in textual sources from antiquity and late antiquity. See D. Rohmann, "Ungleicharmige Waagen im literarischen, epigraphischen und papyrologischen Befund der Antike", forthcoming (Historia).

32 The spread of the steelyard over a vast geographical area and its persistence over time can be characterized as a complex innovation process in which different subtypes of steelyards emerged and replaced each other. This innovation process is studied in detail by the Topoi junior research group D-5-5. The new findings concerning unequal-arm balances presented in this article are a result of this research agenda.

33 In equal arm-balances, the weight of the instrument itself has an influence on its operation too, although not on the equilibrium configuration. In the bismar, the influence of the dead weight of the instrument is handled in the gauging of the scale.

Fig. 5 | Roman steelyard from Pompei.

In the simplest case, a steelyard is a beam divided into two unequal parts by a fulcrum. The longer arm, referred to as the scale-arm, carries the counterpoise and the scale, the shorter arm, referred to as the load-arm, carries some sort of load suspension. The scale of such a balance should ideally start at zero and run up to a certain maximum weight, corresponding to the expected weight of the largest load to be weighed. Optimally, the zero point of the scale should be close to the fulcrum as then the full length of the scale arm is exploited, resulting in a better resolution and a greater ease of weighing.

Already in realising such a simple construction, a number of constraints need to be observed. The zero point of the scale, i.e. the position in which the counterpoise must be hung so that the unloaded balance is in equilibrium, can be on the scale arm if and only if the centre of gravity of the instrument without the counterpoise is located on the load arm. Due to the unequal division of the beam, this will usually not be the case and the position of the centre of gravity needs to be varied. Varying the weight of the load suspension usually does this. The largest weight determinable with the instrument obviously depends on the division of the beam by the position of the fulcrum, as well as on the weight of the counterpoise. The variation of each of these two design parameters, however, in turn affects the zero position of the scale. The division of the beam affects the position of the centre of gravity with respect to the fulcrum, and the heavier the counterpoise, the closer to the fulcrum the zero point of the scale will be for a given position of the centre of gravity.

The complications are dramatically enhanced when, as is the case for the majority of the finds from the period in question, a second fulcrum and thus a second scale is introduced.[34] Here the additional condition that the scales have to be harmonised, i.e. that the minimal weight that can be determined using the second fulcrum should be slightly smaller than the maximum weight of the load determinable with the first fulcrum, comes into play. Hence, in such balances, an optimal position for the second fulcrum exists. If this position is exceeded and the second fulcrum moves closer to the load suspension, a non-functional balance with a gap in its weighing range results. From a modern perspective

34 Whereas the earliest preserved steelyards all have two fulcra, instances of later types tend to have three fulcra. For a typology of steelyards see Franken 1993. A new catalogue is in preparation and will be published soon. A prototype can be accessed via the webpage of the Topoi junior research group D-5-5: http://www.topoi.org/project/d-5-5/ (visited on 15/08/2016).

the optimal position for the second fulcrum depends in complicated fashion on many factors, including the division the beam, the position of the centre of gravity, and finally the ratio of the weight of the balance to the weight of the counterpoise.

An analysis of the steelyards from the Roman period has shown that their makers were able to solve the ensuing problems such as the ones alluded to above in a consistent, remarkably ideal fashion. They were systematically able to produce steelyards in which the position of the counterpoise in unloaded equilibrium is at the very beginning of the scale arm and whose second fulcrum is positioned such that the two scales harmonise perfectly. We are only beginning to understand how this and a great range of additional problems were solved explicitly and which mechanical knowledge this embraced. Suffice to say for the present purpose, the solutions were not, and indeed could not, have been obtained by trial and error with the individual objects. Rather, the preserved steelyards obey certain general principles, i.e. they show repeating complicated patterns in the relations between the relevant design parameters. These regularities can be straightforwardly interpreted as the result of recurrent similar actions in their production, which themselves are the external consequence of the sequential execution of procedural rules. Even today the manufacture of steelyards in some parts of the world is regulated in such a fashion.[35]

Among the rules that were applied are such that embrace variations contingent on prior choices, which themselves depend on the specific purpose of the balance to be built. As a consequence the relationship between different objects produced according to the same set of rules is not immediately apparent: they are in particular not necessarily geometrically similar. Thus, whereas it is conceivable that individual steelyards could have been produced by copying, the fabrication of a broad range of application specific steelyards as it is evidenced in the Roman Empire at remote distances and time intervals is only possible if these rules were explicated and diffused in the context of production. It can indeed be argued that the steelyard as a technological innovation could only successfully take hold once the conditions for diffusing and transmitting such complex knowledge across larger geographical areas and over longer periods of time were given, i.e. against the backdrop of the production infrastructure of the Roman Empire. This production infrastructure constitutes the additional regulatory module that made the success story of the Roman steelyard possible in the first place.

9 The role of infrastructures as inheritance systems for technology

The Roman production infrastructure that, as argued above, enabled the introduction and spread of the steelyard, had itself emerged on a high plateau of technical capabilities and the resources connected with them that had developed since the fourth century BC in the Mediterranean region. The Hellenistic period, in particular, can be seen as an era of technological boom. Technological innovations such as the gearwheel, water pumps, cylindrical screws with bolts, or the dioptra can all be dated back to the Hellenistic period. Alexandria and its network, to which the Syracuse of Archimedes also belonged, was the basis and the institutional reference point for all these innovations and also for the engineers and scholars who investigated them.[36] Technology was then boosted by the need to realise and spread the powerful infrastructure for the military, political, and economic maintenance of the Roman Empire.

Roads and water supply systems could only be built using reliable machines. However, mining activities also caused machine technology to receive the greatest attention and

35 See Renn and Schemmel 2000.

36 For Hellenistic technology, see especially chapter four of Russo 2004. See also Schürmann 1991.

became part of a self-reinforcing mechanism, since the metal technology also underlying the production of weapons and machinery (including pumps and steelyards) would be unthinkable without it. The Roman Empire saw something akin to the creation of a military-industrial complex centred on metal production that also became a presupposition for the widespread production and use of steelyards.[37] From an economic perspective, machines vastly increased the possibilities for more income because they enabled mining activities in regions and contexts that were otherwise not exploitable. In his in-depth analysis of several techniques of hydraulic mining and ore-processing applied by Romans in the Iberian peninsula and what is now French territory (also by means of private capital), the economic historian Andrew Wilson does not hesitate to speak about peaks of mining production that did not reach the same level again until the Industrial Revolution, and in particular, that are only rivalled in their dependency on advanced technology by the modern era.[38] We can thus see that the Roman steelyard, just as every technical product, is associated with a network of production conditions that constitute its variable inheritance structure. Changes in this network may change the product and vice versa. Studying these mutual influences is an ongoing subject of research.

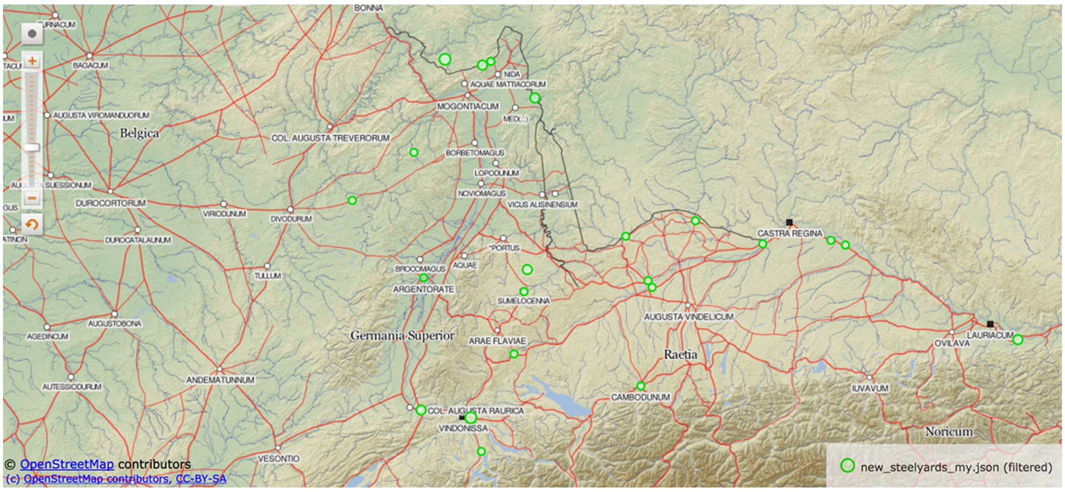


Fig. 6 | Find-spots of iron steelyards of the first and second centuries CE mapped onto the *Digital Atlas of the Roman Empire* (http://dare.ht.lu.se). Forged iron steelyards have been found only north of the Alps. Their spacial as well as temporal distribution implies a close connection of their production and use to Roman military infrastructure.

In summary, bismar-type balances could be improvised, while the production of Roman steelyard required a rather elaborate societal and cognitive infrastructure. Compared to the bismar, the steelyard posed higher requirements regarding the production knowledge which were, however, compensated by evident advantages in its use. It is more adaptable to different weighing purposes and generally more accurate and simpler to handle than a bismar. That the steelyard, despite these advantages, could apparently not establish itself against the bismar in India may thus be explainable by the lack of an infrastructure capable of transmitting and diffusing the required complex production knowledge. One of the

37 See Sommer 2013, chap. 4.

38 See Wilson 2002. Wilson's paper is an effective response to the widespread idea that technological innovation and economy were not linked in antiquity. This idea was diffused by M. I. Finley. See in particular Finley 1965. For a large study on the relationship between technology and economy in antiquity, see Lewis 1997.

open and challenging questions in the evolution of weighing technologies is how the Roman steelyard could nevertheless survive the decline of the Roman Empire and become an important asset in the Islamicate empires, in China, in the European Middle Ages and the Renaissance, and continue to be produced and used essentially until today.[39]

10 The unexplored interaction of technical and theoretical knowledge

The transition from the bismar to the steelyard also left its traces in the theoretical writings on mechanics. When referring to unequal-arm balances, the author of the *Mechanical Questions* and later authors such as Vitruvius or Hero of Alexandria were indeed treating different instruments. If their theoretical treatments were in some way informed by the technological knowledge associated with the respective instruments, one needs to take into account that such knowledge is quite distinct for the bismar and the steelyard. Although, due to the relatively simple construction of the bismar, the passage in the *Mechanical Questions* (besides giving an explanation of the operational principle) could thus function also as a representation of the technical knowledge required to build such an instrument, this is no longer the case for Vitruvius' treatment of the steelyard. Hero squarely addressed the difference between theoretical principles and the actual construction of a balance:

> Some people believe that when in balances the weights are in equilibrium to the weights, the weights have to be to the distances in the said inverse proportion. This can generally not be maintained …[40]

In the rather ingenious proof following this passage, Hero shows that a simple form of the law of the lever does not always adequately describe equilibrium when the deadweight of the balance beam is accounted for. The configuration discussed in his proof clearly corresponds to a steelyard even if it is not explicitly referred to as such. Thus, Hero here addresses what has been identified above as one of the central problems to be overcome when designing and fabricating a steelyard. Whether scientific thought actually influenced the technological transition from the bismar to the steelyard cannot currently be answered and the question may, due to the sparse evidence in our possession, in fact remain unanswerable.

Our studies of the innovation processes of early weighing technologies have drawn attention to yet another question regarding the relation of science and technology in antiquity. The rules applied in producing steelyards are entirely different from the modern physical formula allowing us to express the conditions that a steelyard has to meet in order to actually function as a weighing instrument, yet the application of these rules in the production of steelyards gives rise to what, from a theoretical perspective, must be considered as an almost optimal result. Were these rules established purely on an empirical basis or did theoretical knowledge play a role in their formulation? We have reasons to be confident that we will be able to answer such fundamental questions in our further research.

39 Fort the production of steelyards in modern day China see Renn and Schemmel 2000.
40 See Heron of Alexandria 1900, p. 86.Translation by the authors.

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