



Bronze Age weight systems as a measure of market integration in Western Eurasia

Nicola Ialongo^{a,1} , Raphael Hermann^a , and Lorenz Rahmstorf^a

^aSeminar für Ur- und Frühgeschichte, Georg-August-Universität Göttingen, D-37073 Göttingen, Germany

Edited by Kristian Kristiansen, Goteborgs Universitet, Gothenburg, Sweden, and accepted by Editorial Board Member Elsa M. Redmond May 20, 2021 (received for review March 26, 2021)

Weighing technology was invented around 3000 BCE between Mesopotamia and Egypt and became widely adopted in Western Eurasia within ~2,000 y. For the first time in history, merchants could rely on an objective frame of reference to quantify economic value. The subsequent emergence of different weight systems goes hand in hand with the formation of a continental market. However, we still do not know how the technological transmission happened and why different weight systems emerged along the way. Here, we show that the diffusion of weighing technology can be explained as the result of merchants' interaction and the emergence of primary weight systems as the outcome of the random propagation of error constrained by market self-regulation. We found that the statistical errors of early units between Mesopotamia and Europe overlap significantly. Our experiment with replica weights gives error figures that are consistent with the archaeological sample. We used these figures to develop a model simulating the formation of primary weight systems based on the random propagation of error over time from a single original unit. The simulation is consistent with the observed distribution of weight units. We demonstrate that the creation of the earliest weight systems is not consistent with a substantial intervention of political authorities. Our results urge a reevaluation of the role of individual commercial initiatives in the formation of the first integrated market in Western Eurasia.

Western Eurasia | Bronze Age | market integration | weight systems | trade

The invention of weighing technology around 3100 to 3000 BCE marks a turning point in economic history (Fig. 1): For the first time, trade could rely on an objective frame of reference to quantify the value of commodities (1, 2). The evidence shows a gradual but linear diffusion of weighing technology (Fig. 2A) that produces a new weight system whenever it reaches a new macroregion (Fig. 3). By the second millennium BCE, merchants could potentially trade anywhere in Western Eurasia simply by knowing the conversion factors of a multitude of local weight units (3). Hence, the formation of weight systems represents a footprint of commercial interaction in the Bronze Age world.

At present, our knowledge on the origins of weight systems is limited, and we still do not know how and why different units emerged in different regions. Previous work is largely based on inductive, nonverifiable methods, and while methodologically sound studies are slowly growing in number, they are still limited to small regions and short periods (4–6). Here, we present a comparative study of all the weight systems that were in use between the Indus Valley and Atlantic Europe during the third and second millennia BCE.

A crucial question is whether weight units were enforced by political authorities or customarily regulated by networks of merchants. In the third and second millennia BCE, weighing technology was widely used by both public administrations (7, 8) and private merchants (9, 10). Cuneiform texts do not shed light on the origins, as weight systems are very rarely mentioned before ~2600 BCE (11); however, in Greece (6) and Egypt (12), written evidence appears long after the earliest archaeological attestations. The first institution of a “royal standard” dates only to the end of the third millennium BCE in Mesopotamia (2112 to 2095 BCE) (13).

The very phrasing of the reform implies that the king did not even introduce a new unit but simply ratified as official a value that was already widely used (14). Furthermore, the diffusion of weighing technology in prestate societies in Europe and Anatolia indicates that the existence of a state was not even a requirement.

Once weighing technology became widespread, strong public institutions—where they existed—would have probably played a role in regulating weight systems. In Mesopotamia, for example, the existence of public institutions with outstanding economic capacity and a great need for imported goods played a substantial role in creating opportunities for trade. In the Ur III period (2112 to 2004 BCE), merchants worked ~50% of their time for the state, while they pursued personal interests for the remaining 50% (10). In the Old Assyrian period (~2000 to 1700 BCE), merchants operated in a network spanning Anatolia and Northern Mesopotamia. Central authorities could regulate trade by maintaining roads, providing insurance against theft, and establishing political treaties between potentially conflicting polities (15). The state did not directly “manage” merchants, but since it was the biggest buyer on the market, many merchants were inevitably reliant on it in order to conduct their businesses. The interaction between public institutions and private merchants likely created a feedback cycle that helped regulate weight systems. Direct regulatory intervention, however, was only possible within the state's territorial jurisdiction and only in those instances in which the state was either directly involved in the transaction or when the transaction took place in

Significance

Increasing evidence shows that Bronze Age civilizations in Western Eurasia were economically interdependent for the procurement of essential raw materials. While this phenomenon hints at the possible formation of the first integrated market in history, recent models do not tackle its macroeconomic implications. Here, we address the customary regulation of weight systems as a measure of market integration. We show that Western Eurasian weight systems are consistent with the origin from a single unit. The information flow was efficient enough to regulate the statistical dispersion of weight systems on a continental scale, without any substantial intervention from political authorities. We argue that this suggests that the market had a concrete potential for an efficient reaction to price fluctuations.

Author contributions: N.I. designed research; N.I., R.H., and L.R. performed research; N.I. and R.H. contributed new analytic tools; N.I., R.H., and L.R. analyzed data; and N.I., R.H., and L.R. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. K.K. is a guest editor invited by the Editorial Board.

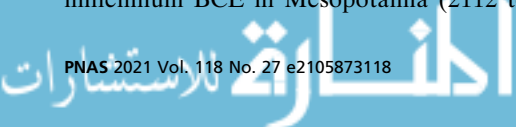
This open access article is distributed under [Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 \(CC BY-NC-ND\)](https://creativecommons.org/licenses/by-nc-nd/4.0/).

See [online](#) for related content such as Commentaries.

¹To whom correspondence may be addressed. Email: nicola.ialongo@uni-goettingen.de.

This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2105873118/-DCSupplemental>.

Published June 28, 2021.



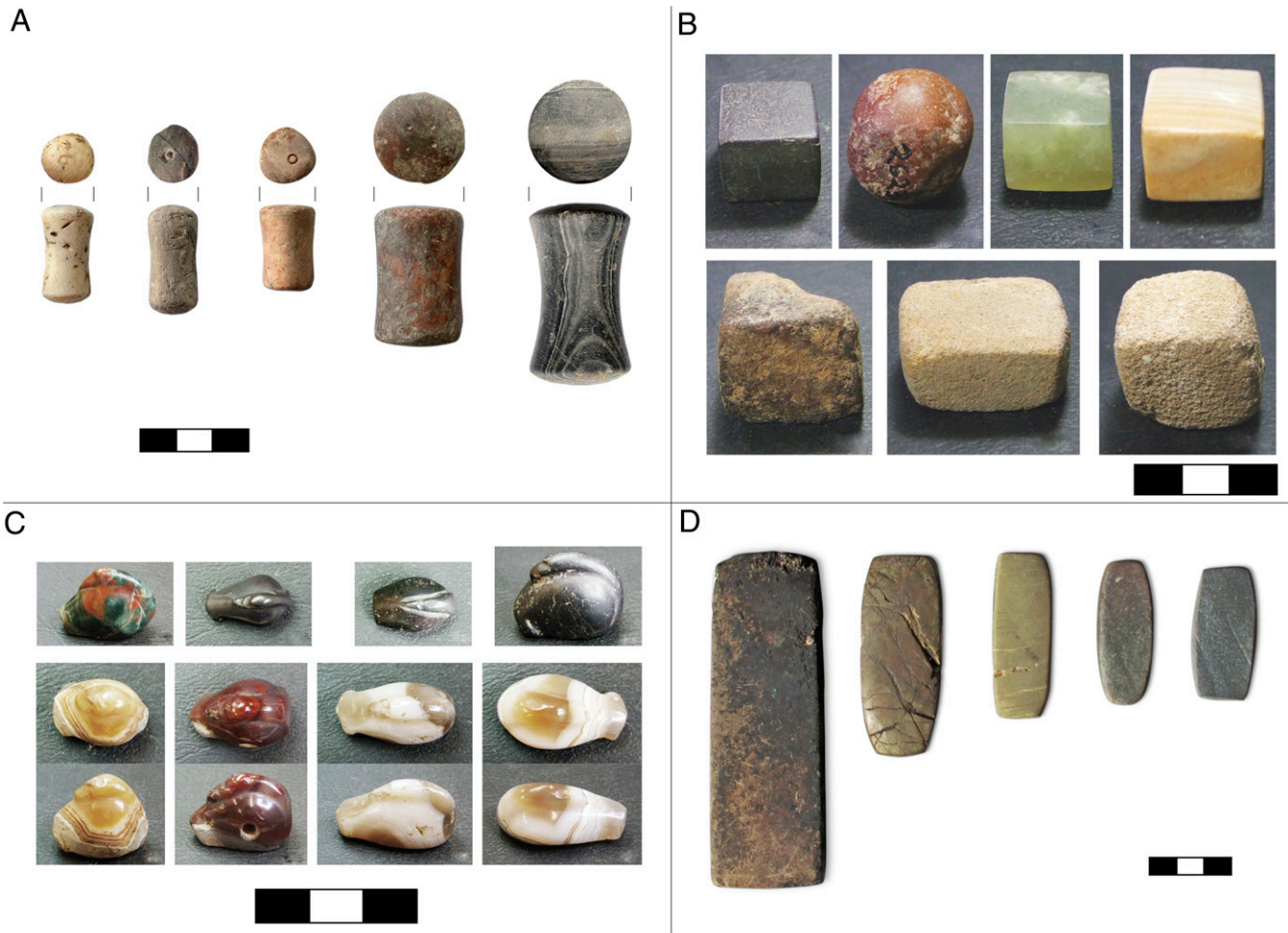


Fig. 1. Examples of Western Eurasian balance weights of the Bronze Age. (A) Spool-shaped weights from Tiryns, Greece (photograph by L. Rahmstorf). (B) Cubic weights from Dholavira, India (photograph by E. Ascalone, Department of Humanities, University of Roma Tre, Rome, Italy). (C) Duck-shaped weights from Susa, Iran (photograph by E. Ascalone). (D) Parallelepiped weights from Lipari, Italy (photograph by N. Ialongo). Approximate scale.

an officially regulated context, such as city markets (16). Official weight-regulation did not occur when merchants were dealing privately with one another or when they were trading with foreign

partners from countries where central institutions were either less invasive or did not exist at all. Moreover, the fragmentation of the political landscape of the Eastern Mediterranean toward the end of

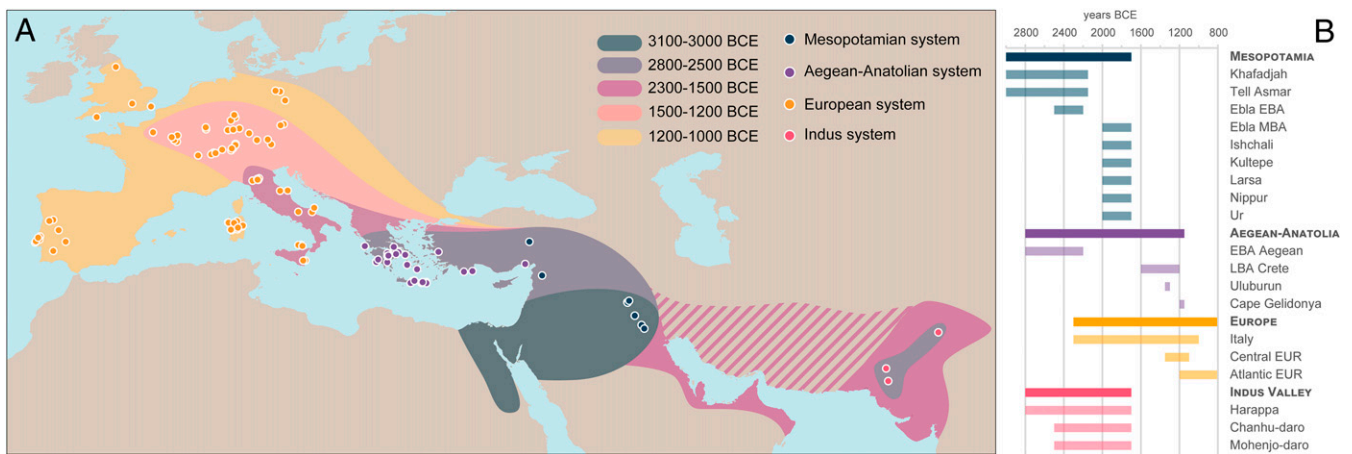


Fig. 2. (A) Diffusion of weighing technology. The gradient illustrates the time scale of the spread of weighing technology as suggested by the archaeological evidence. The dots indicate the find spots of the balance weights included in the sample of the statistical analyses. The colors of the dots indicate the regional weight system to which they are assigned. (B) Chronology of the analyzed datasets.

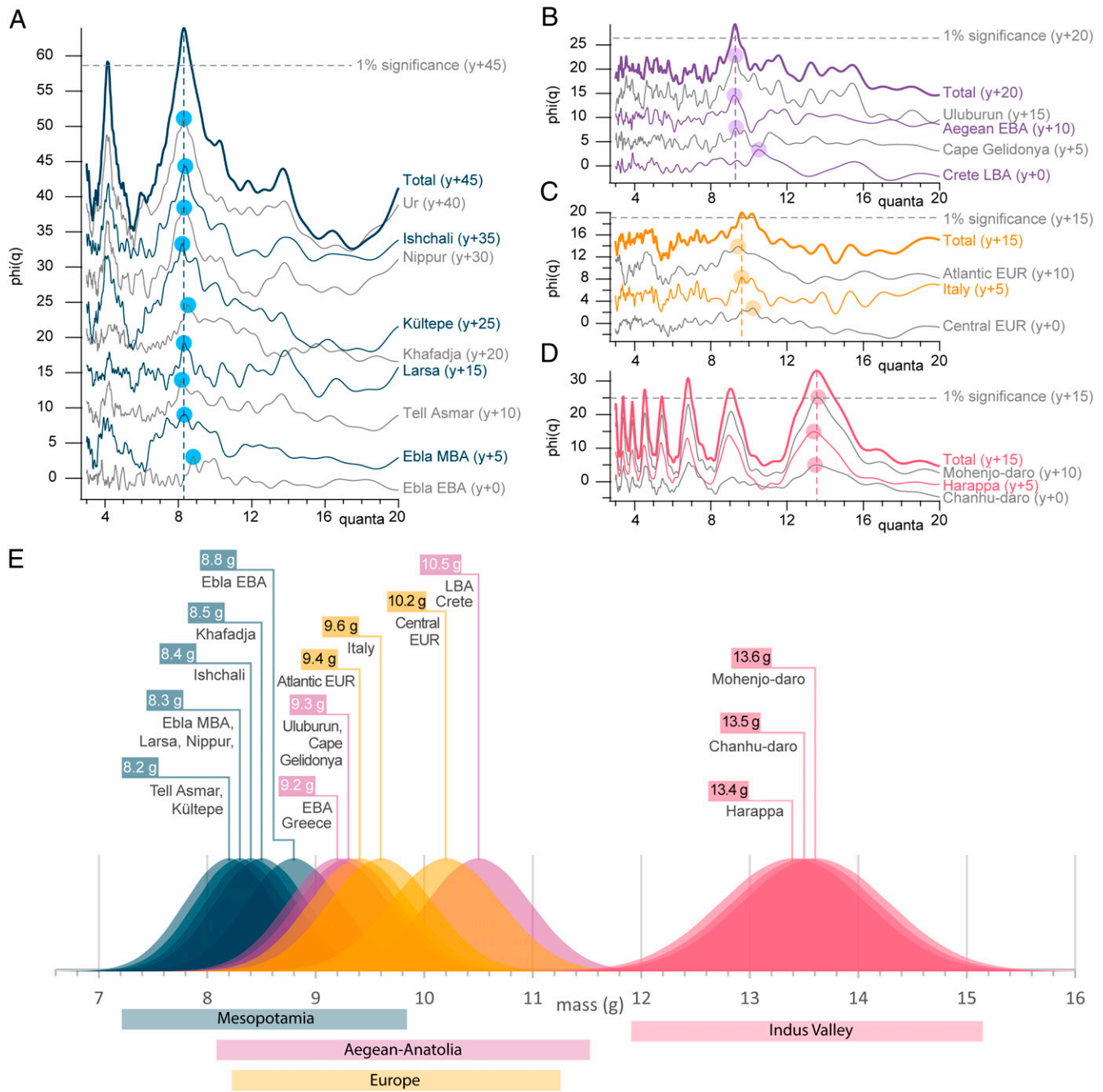


Fig. 3. Western Eurasian weight units. (A–D) CQA for (A) Mesopotamia, (B) Aegean-Anatolia, (C) Europe, and (D) Indus Valley. The y values are offset in order to enhance visibility; the offset value of each series is specified on the figure. The horizontal dashed lines indicate the 1% significance level. The vertical dotted lines indicate the best-fitting quantum for the total sample of each system; the best-fitting quanta of each series are indicated by colored circles. (E) Best-fitting quanta for the Western Eurasian units of the Bronze Age, represented as normal distributions with a CV of 5.4%.

the second millennium BCE may have eventually opened up further opportunities for private entrepreneurship.

Since the evidence is not consistent with a predominant role of public institutions, our alternative hypothesis is that private merchants were the main agents responsible for the diffusion of weighing technology and for the creation and customary regulation of widespread weight systems. The hypothesis is relevant to understand the emergence of long-distance connectivity networks in the Bronze Age, which recent models frame as a Western Eurasian phenomenon (17–19). It has become increasingly clear that local economies were dependent on trade to procure essential but rare raw

materials such as tin (18, 20) and that both Eastern city-states and European village-societies were equally thriving in this reciprocal dependence (17). These observations raise a fundamental question that recent models do not address: if some rare commodities were demanded globally, did their prices follow common trends across the market? Addressing this question is objectively difficult, as direct information on prices is only provided by a few cuneiform archives in Mesopotamia, covering limited territories and short time spans (21). We can, however, approach the issue indirectly. Information theory applied to macroeconomics predicts that market equilibrium is regulated by the distribution of the collective

knowledge about prices (22, 23). In extreme synthesis, the more efficiently information flows, the more efficiently the market will react to price fluctuations. We propose that, for the Bronze Age, one can quantify the efficiency of information flow by measuring the statistical dispersion of weight units on a continental scale. Here, we show that the origin of weight systems in Western Eurasia can be explained with the random propagation of error from a single value, with statistical dispersion remaining at low levels due to an uninterrupted process of self-regulation put in action by networks of merchants over roughly two millennia. We propose that if the information flow was efficient enough to regulate weight standards on a continental scale without public intervention, then it is also possible that the market could react efficiently to local price fluctuations.

We start by outlining the evidence for the diffusion of weighing technology. Then we define the theoretical values of Bronze Age units and calculate their statistical dispersion based on archaeological data and experimental replicas. Based on these figures, we develop a simulation model for the origin of weight systems, and we use it to test our hypothesis.

Results

The Diffusion of Weighing Technology. The first archaeological evidence for balance weights dates to the beginning of the Bronze Age. In Egypt, the earliest weight can be dated to ~3100 BCE (24). In Mesopotamia, the Early Dynastic sites in the Diyala Basin yielded weights dating to ~3000 BCE (25). The absence of weight systems in the Uruk texts suggests that the technology was not yet present in the late fourth millennium BCE (7). The earliest mention of a weight unit in cuneiform texts dates to ~2900 to 2600 BCE (11).

The earliest evidence for Anatolian (26) and Aegean weights (27) dates to ~2900 to 2800 BCE. In Syria, evidence for weights only appears around ~2500 to 2200 BCE (28), but this might be due to the fact that earlier periods are largely underrepresented in Syrian excavations (29). In the Indus Valley, weighing equipment is attested in the late Early Harappan period (~2800 to 2600 BCE) (30). In the Persian Gulf, weighing equipment is documented between ~2500 to 2300 BCE (31), while in Iran there is sparse evidence dating to the first half of the third millennium BCE (32). West of Greece, balance weights are present in Southern Italy by ~2300 to 2000 BCE (33), in Northern Italy by ~1600 BCE (34), and become widespread between Central Europe (35) and Southern England (36) by ~1350 BCE. Weighing technology seems to reach the Atlantic façade toward the end of the second millennium BCE (37). By 1000 BCE, weighing technology is commonly used in Western Eurasia (38).

Definition of Bronze Age Units. Based on Cosine Quantogram Analysis (CQA), we calculated the best-fitting quantum of each regional data set (Fig. 3 A–D). CQA confirms the validity of the so-called Mesopotamian shekel of ~8.2 to 8.8 g (39), the Levantine or Ugaritic shekel of ~9.2 to 9.3 g (40), the Pan-European shekel of ~9.4 to 10.2 g (38), and the Harappan shekel of ~13.4 to 13.6 g (41). The data set of Early Bronze Age Coastal Anatolia is too small to give meaningful results ($n = 21$). The analysis does not provide support for the Eblaite shekel of ~7.8 g and the Anatolian shekel of ~11.75 g (8). The analysis of the Cretan Late Bronze Age sample highlights a quantum of ~10.5 g, one-sixth of the unit of ~54 to 68 g, determined based on marked weights. The Cycladic sample of the same period does not show any well-fitting quanta in the shekel range. The Mesopotamian, Indus, Aegean-Anatolian, and European systems all emerge together with the first adoption of weighing technology.

Measuring Error: Weight Units as Intervals. CQA can identify best-fitting quanta that, to some extent, approximate the ideal concept of a unit. These values, however, are far from satisfactory. While

one intuitively tends to think of ancient weight units as exact values expressed in grams, these values are not in fact the unit but simply inaccurate attempts to fix indeterminate, normally distributed intervals that their original users always perceived as “1” (39, 42). Units of measurements do not exist without error; hence quantifying error is necessary to allow comparability.

Based on inscribed weights, we calculate that the coefficient of variation (CV) of Bronze Age units was between ~5 and 6%. We expect two concurring factors to produce this dispersion. The first factor is the instrumental error of balance scales, an issue of which ancient users were already aware (7, 16): A craftsman will make a new weight starting from a preexisting weight that they will use as a model, hence producing instrumental error. The second factor is the randomness of the selection of the weight that is used as a model to make a new one: since official standards do not exist for primary weight systems (or they are not available for everyone to use), the model-weight will be randomly picked from a normally distributed population, with a chance that it will be picked from one of the “tails,” hence producing further error that will be summed to the instrumental one. In order to test our expectations, we designed an experiment that could reproduce these conditions. We produced 100 replica weights, each time randomly selecting the weight meant to serve as the model. The experiment gives a figure for the instrumental error of Bronze Age balance scales of $\pm 3.4\%$, which is remarkably close to the figure of ~3% reported by cuneiform texts of the third millennium BCE (7). The random selection of model weights further propagates the error, ultimately producing a normally distributed sample with CV 5.4%. The result is consistent with the figures obtained for the archaeological weights and confirms the expectations for the sources of error of ancient units.

Creation and Regulation of Weight Units. When plotted as normal distributions with a CV of 5.4%, the weight units of Western Eurasia are sharply divided into two groups (Fig. 3E): on the right side, the Indus unit remains isolated, while all other units between Mesopotamia and Atlantic Europe form a cluster on the left side, between ~7 and 11 g. The error ranges in this cluster overlap to the extent that supposedly different units are in fact barely distinguishable from one another. In other words, large portions of the intervals that were accepted as valid units in one region were also accepted in another region with an allegedly different unit. This means that a single merchant could potentially travel from Mesopotamia to the Aegean, and from the Aegean to Central Europe, and never change their set of weights while simply relying on approximation. The same was not possible between Mesopotamia and the Indus Valley.

As weighing technology gradually spreads west of Mesopotamia, new units emerge along the way, slightly different from the closest preexisting ones but still largely compatible. At the same time, the strikingly unique Indus unit stands out not only numerically, but also geographically, as it is separated from Mesopotamia by a large void of documentation corresponding to the Iranian Plateau (Fig. 2A). These observations raise a question: can one explain the gradual formation of weight systems between Mesopotamia and Europe as the random outcome of the propagation of error from a single original value? We hypothesize that, whenever weighing technology is adopted in a new region for the first time, a new unit will emerge, based on a random variation of the unit in use in the region from where the technology is imported. We assume that merchants are the main agents responsible for the spread of the new technology and for the customary normalization of the new unit. In order to test the hypothesis, we designed a model to simulate the creation of new units.

Our model simulates the formation of 100 new units between ~3000 and 1000 BCE at an ideal interval of 20 y (Fig. 4). We use the term “system” to designate a network of merchants active in a given territory, who make use of a similar unit (i.e., a “weight system”). “System 0” is the system where weighing technology

was invented, represented in our model by the Mesopotamian system (~8.3 g). The error figures are based on archaeological observations and experimental results. The model can be summarized as follows:

1. A few merchants from System 1 begin crafting the first weights based on a random selection of weights picked from merchants from System 0. Each new weight will be affected by instrumental error of approximately $\pm 3\%$ (Fig. 4A).
2. The first weight-users in System 1 will start trading with peers from the same system, hence spreading weighing technology (Fig. 4B).
3. A few merchants from System 1 begin weight-based trade with peers from System 2, triggering the replication of the entire process (Fig. 4B and C).
4. Every time weighing technology is transmitted to a new system, a slightly different unit will emerge. The market will tend to reject weights that deviate too much from the customarily

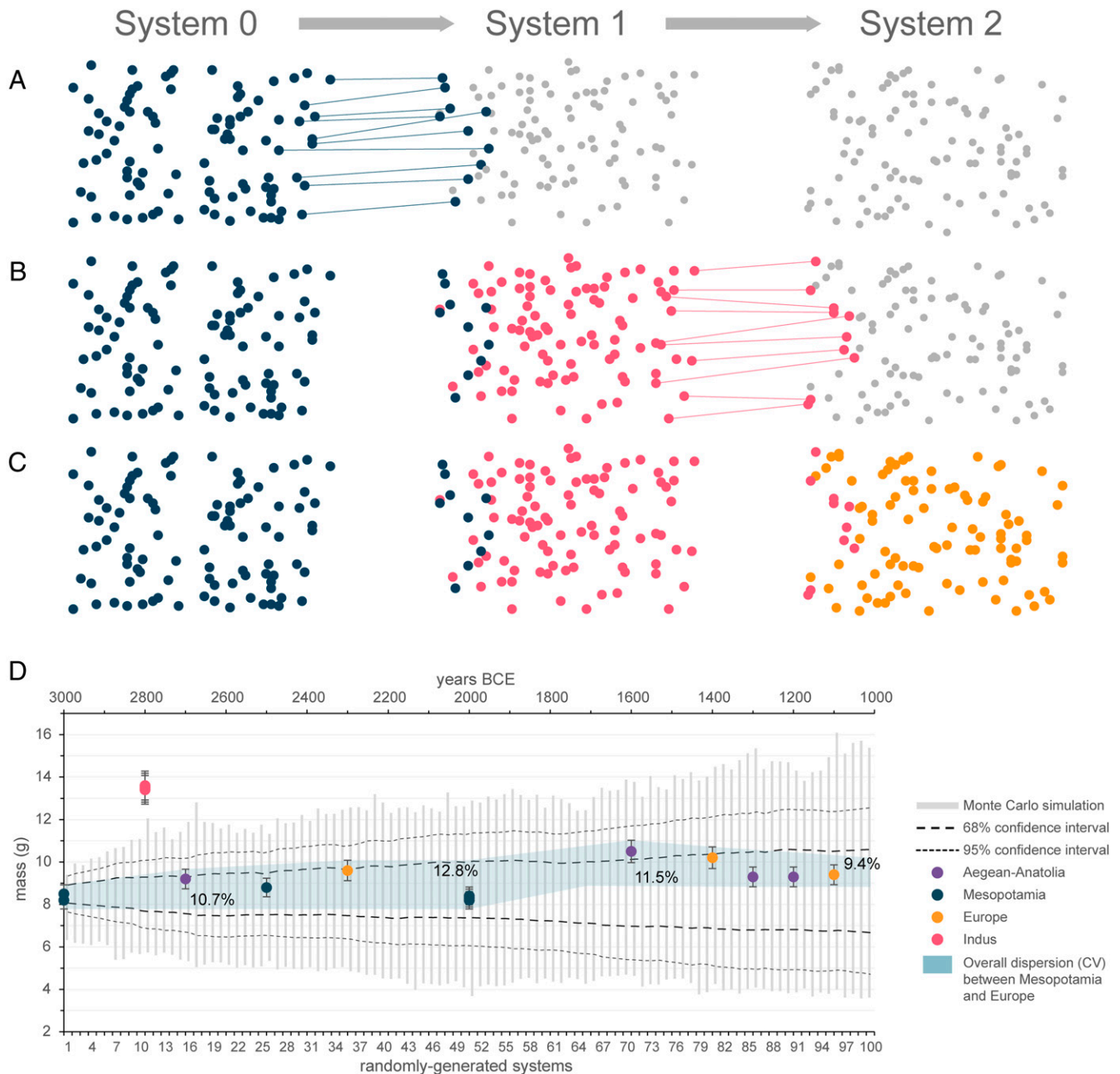


Fig. 4. The origin of weight systems: simulation model. (A–C) Schematic representation of the generation, transmission, and distortion of weight systems described in the text. Each system is composed of 100 randomly distributed dots, each representing a single merchant possessing a single balance weight. Different colors represent different units. Gray dots represent merchants who do not use weighing equipment yet. (D) Outcome of the simulation model. Colored dots: Bronze Age weight units, with 5% error bars. Gray bars: outcome of the Monte Carlo simulation. The dashed lines represent the 68% (1 SD) and the 95% (2 SDs) CIs of the dataset generated by the Monte Carlo test. The overall dispersion takes into account the chronological intervals illustrated in Fig. 2B. The CV values describe the dispersion at given points in time. (Upper) Time scale of the archaeological units (the earliest date of the chronological range is displayed). (Lower) Sequential numbering of the randomly generated systems. (Left) Mass of the archaeological and simulated units in grams.

accepted norm, thus keeping the overall dispersion of new units at a relatively low level (CV ~5%).

Step 1 describes how error is generated and how a new unit will diverge from the previous one. Since the first weights will be selected randomly, there is a chance that they will be picked from the tails of the preexisting distribution, hence skewing its mean. The average value of the first weights will then form the initial core of the unit that will eventually become the norm in System 1 (steps 2 and 3). A Monte Carlo simulation reiterates the process 1,000 times. Our objective is to obtain a predictive model to explain the formation of the weight systems in Fig. 3.

The Monte Carlo simulation produces 100 data sets, whose dispersion tends to grow at each iteration, thus simulating the range of divergence from the original value through time (Fig. 4D). The model correctly predicts the formation of primary weight systems between Mesopotamia and Europe, with almost all units falling within the 68% CI and only one within the 95% CI.

Discussion

Excluding the Indus Valley, the total statistical dispersion of Bronze Age units ranges between ~9 and 13% (Fig. 4D). Despite the continuous creation of new units, the dispersion remained approximately constant for ~2,000 y and over a linear distance of roughly 5,000 km. We interpret these results as the outcome of intentional regulation. The potential error was probably constrained by systematically excluding deviant weights, thus preventing the uncontrolled proliferation of weight systems. Since no public authority existed that could enforce weight systems over such a vast area and for such a long period, we conclude that this must have been the outcome of market self-regulation. The formation of weight units between Mesopotamia and Europe can be explained as the outcome of a gradual process of technological transmission driven by the private initiative of merchants, partly affected by the random propagation of error and largely regulated by the market. The simulation also shows that the Indus unit cannot derive from the Mesopotamian system. Even if one assumes that the lack of evidence in the Iranian Plateau is due to a lack of research, the Indus system is too different to have originated only by progressive error in a relatively short time. Hence, the Indus Valley likely developed an independent weight system. This could hint at the existence of a Central Asian market for which, however, we do not have evidence yet for the third millennium BC.

While different goods were likely exchanged in long-distance trade, the evidence suggests that metals were the main commodities responsible for the normalization of weight systems. Economic cuneiform texts report metals as the most frequent objects in weight-based transactions, with silver frequently used as weighed currency (43), while bronze in preliterate Europe was likely intentionally fragmented in order to comply with weight units (44).

Our results demonstrate that weight units were originated and customarily regulated by networks of merchants. Public institutions were also important agents in this process, but their role was limited to those regions and periods in which strong institutions actually existed. While the spread of weighing technology was likely the outcome of a diffusion process, the formation of new units was determined neither by diffusion nor by imposition but only by the continuous negotiation of how much deviation the market could tolerate before the norm was violated. The statistical dispersion of weight units provides an approximate quantification of the potential for market integration: if information flow was efficient enough to keep dispersion at such low levels over such a vast area, it means that the trade network could theoretically rely on efficient reactions to price fluctuations.

As long as markets regulate weight systems, the spread of a weight system is an approximate measure of the geographical extent of the market by which it is regulated. Our results suggest the existence of either three individual, albeit interconnected, markets

(Mesopotamia, Aegean-Anatolia, and Europe) or a single Western Eurasian market, the difference being merely a matter of perspective. Our macroeconomic approach focuses on crucial functions of economic systems that traditional archaeological models are not well-suited to address. Market equilibrium and opportunistic economic behavior are some of these functions. The possible existence of an integrated market is not in contradiction with mainstream models that see the Bronze Age world as tied together by a network of social and political relationships. In our view, global trade was the background against which these bonds were shaped. Widespread weight units could not have formed without a critical mass of trade agents, acting within an interconnected network. This urges a reconsideration of private commercial initiative in the formation of connectivity networks in Bronze Age Western Eurasia.

Materials and Methods

The Sample. The sample comprises 2,274 balance weights from 127 sites (Dataset S1) and only includes objects with known mass that are either complete or that could be reconstructed via three-dimensional (3D) scanning and modeling (38). The sample was collected from the most relevant contexts in Western Eurasia, between ~3000 and 1000 BCE and is divided into four geographic subsets, which we refer to as "systems": Mesopotamia (including Syria and Central Anatolia, for historical reasons; $n = 1,139$), the Aegean Sea and Coastal Anatolia ($n = 505$), Europe (excluding Greece; $n = 222$), and the Indus Valley ($n = 408$). The chronology of each sample is illustrated in Fig. 2B. The data from Mesopotamia and the Indus Valley come from extensively excavated Bronze Age cities, each providing large numbers of weights. Since these big sites provide highly significant data sets, the sampling in these regions did not include isolated finds. The data from Ur (5), Nippur (45), Larsa (46), Ebla (28), and Kültepe (47) are published. The previously unpublished data from Tell Asmar, Khafajah, and Ishchali were recently documented by L. Rahmstorf and N. Jalongo at the Oriental Institute of Chicago. The weights of the Indus Valley come from the sites of Harappa, Chanhu-daro, and Mohenjo-daro (48). The European data set was collected through systematic sampling of all the existing evidence, both published and previously unpublished (38). The data from the Aegean and coastal Anatolia include ~50 sites of the Early, Middle, and Late Bronze Age (6) and the Late Bronze Age shipwrecks of Uluburun and Cape Gelidonya (49). Egypt could not be sampled, as most weights come from undated contexts of very old excavations (50, 51). The Persian Gulf and Iran do not produce a sample large enough for statistical analyses. The complete database is included in Dataset S1.

CQA. CQA allows to determine if a sample of metrical observations is the product of an underlying unit by looking for "quanta" in a distribution of mass values (52). It tests whether an observed measurement x is an integer multiple of a quantum q plus a small error component ε . x is divided for q , and the remainder (ε) is tested. Positive results occur when ε is close to either 0 or q (i.e., when x is [close to] an integer multiple of q):

$$\phi(q) = \sqrt{2/N} \sum_{i=1}^n \cos\left(\frac{2\pi\varepsilon_i}{q}\right),$$

where N is the sample size, and $\phi(q)$ is the test statistic (Dataset S2).

Monte Carlo tests for statistical significance can exclude the occurrence of false positives. The null-hypothesis is that the sample is randomly constituted (i.e., that the observed quantal configuration is only due to chance). Following Kendall's method, a simulation of randomly generated data sets is produced. Each original sample is randomized by adding a random fraction of $\pm 15\%$ to each measurement. The simulation is applied 1,000 times for each sample, and each generated dataset is analyzed through CQA. If equal or better results occur more often than in 1% of iterations, it cannot be excluded that the results are simply due to chance, and therefore they should be rejected. If better results occur in less than 1% of the iterations, then the null-hypothesis is rejected.

The basic weight units of the Bronze Age are often referred to as shekel, ranging from ~8 g to ~14 g. Other units belong to different orders of magnitude, such as the grain (less than 1 g), the mina (~470 to 510 g), and the talent (~20 to 30 kg). In the Late Bronze Age Aegean, a relatively large sample of inscribed weights points to a unit of ~54 to 68 g (6). Our aim is to target only the order of magnitude of the fundamental unit shekel, as it is represented in every subregion and in every period addressed by this study

and hence offers the best basis for comparisons. In order to obtain comparable results and avoid false positives and negatives, the CQA was limited for every sample to a range comprised between 7 and 200 g (44).

Accuracy of Archaeological Weights. The only way to empirically calculate the dispersion of Bronze Age units is through weights that bear inscriptions indicating their nominal value. The ideal unit x is calculated simply by dividing the mass w for the fractional value f , indicated by the inscription:

$$x = w/f.$$

The Mesopotamian and Late Bronze Age Aegean units show CV of, respectively, 6.1% and 4.7% (Fig. 5 A and B). The marked Early Bronze Age weights from Greece indicate a CV of 10.5% for the Aegean-Anatolian shekel, but the sample is too small to consider this result reliable (Fig. 5C). This method is accurate, but it relies on a very small sample, as inscribed weights are very rare. In our sample, only 82 weights have inscriptions (~3% of the total), 57 of which come from Mesopotamia and 25 from Greece.

Quantification of Error Based on Experimental Replicas. In order to verify the validity of the archaeological observations, we devised an experimental study of balance weight production. We hypothesize that dispersion was determined by two main factors: 1) a measurement error in the (re)production of balance weights and 2) the randomness of the selection of the weights to be reproduced.

To test the hypothesis, we produced 100 replica weights using a selection of authentic replica bone balance scales (53) (Fig. 6) (Dataset S3). The first weight (Weight 1) has a mass of 153.24 g and served as a model for Weight 2. Weight 3 was modeled after an item randomly selected from the previous two, Weight 4 after an item randomly selected from the previous three, and so on. By noting down every step, we were able to map the propagation of error (Fig. 5D).

The mass values are normally distributed between 137.77 g and 178.67 g, with an average of 150.45 g and an SD of 8.16 g (CV 5.42%). The instrumental error of the balance scale is $\pm 3.4\%$; since an equal-arm balance effectively provides a null measurement, the final error is always proportional to the value that is being equalled. The distribution has a cutoff left tail (Fig. 5E), correlated to the manufacturing technique. When grinding the replica blanks, we progressively removed small amounts of material until the scales showed an equilibrium (Fig. 5F). This involuntarily created a slightly positive bias.

Whereas the majority of the replicas fall within the usual error of up to 5%, five of the weights (IDs 71, 80, 82, 84, 87) have a higher error of up to 14% (20

g) compared with the original they were based on, despite the balance scales seemingly showing an equilibrium. This could have been the result of various factors such as a build-up of stone dust on one of the leather balance pans. Importantly, however, handheld balance scales always include a certain amount of human bias: The scales are in equilibrium when the human eye determines the beam to be perfectly horizontal. This is entirely down to each individual's perception, which is liable to error (53). This perception bias was already known in antiquity and is the topic of disputes between trader and customer in multiple depictions from the Egyptian Old Kingdom (54, 55). In addition, also disputes over capacity measures are recorded in ancient Egyptian sources with deviations of 5% or even more (56). In practice, a significantly "off" balance weight would become noticed as soon as the trader who made it used it in transaction with another trader. In order to maintain reciprocal trust, the trader would discard the faulty weight.

Simulation Model. We designed a simulation model in order to test if the archaeological data are consistent with the hypothesis that 1) Western Eurasian units originated by propagation of error from a single original value, and 2) the statistical dispersion was customarily regulated by the market. The model is based on Microsoft Excel's random number generator and *norm.inv* function, which produces normally distributed data with random probability given a mean and a SD (syntax: probability,mean,standard_dev) (Dataset S4). We imagine 100 systems, each composed of 100 agents. "System 0" is where weighing technology was first invented and is modeled after the Mesopotamian unit with mean 8.3 g and a CV of 5%. The first 10 variables of System 1 (B2:B11 in the spreadsheet) are picked from the last 10 variables of System 0 (A92:A102), whereby each new variable is calculated as a value in a normal distribution with random probability, mean corresponding to the value of the variable from which it is picked, and a CV of $\pm 3\%$. Since the variables of System 0 are generated randomly, picking the last 10 equals a random selection. The rest of the variables of System 1 (B12:B102) correspond to a normal distribution with random probability, CV of 5%, and mean equal to the average value of the first 10 variables (B2:B11). The same procedure is applied to each of the following 98 cases in the simulation. A Monte Carlo simulation repeats the process 1,000 times. The results of the simulation show how the error propagates through systems and are consistent with the archaeological evidence (Fig. 4D).

Data Availability. All study data are included in the article and/or supporting information.

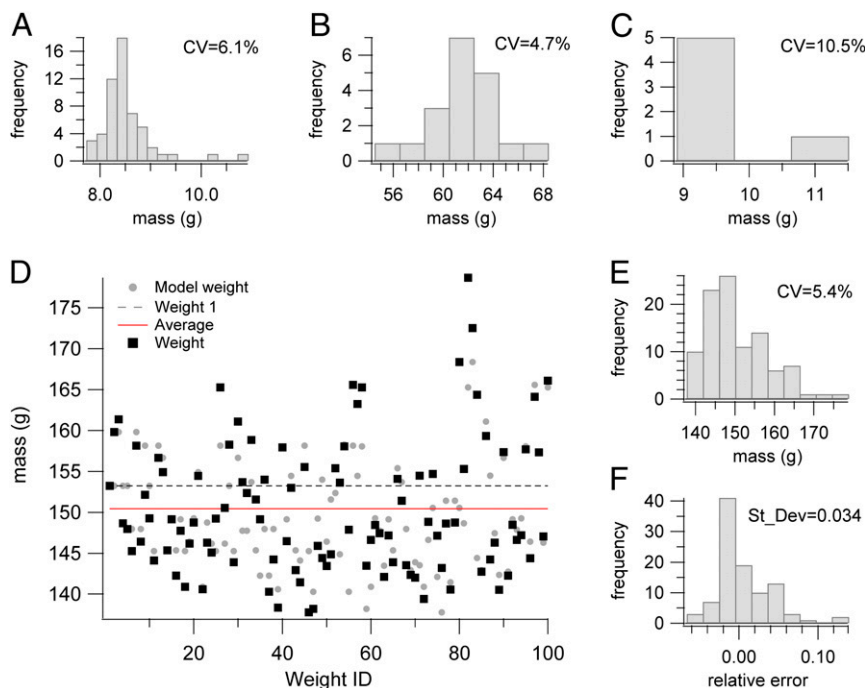


Fig. 5. Statistical dispersion. (A–C) CV based on inscribed weights. (A) Mesopotamia, (B) LBA Greece, (C) EBA Greece. (D–F) Replica weights. (D) Propagation of error for 100 replica weights. For each weight, the mass (black square) and the mass of the weight it was based on (gray dot) are shown. The dashed line indicates the mass of the first weight crafted. The red line represents the distribution mean. (E) CV. (F) Relative error.



Fig. 6. (Left) 100 experimental weight replicas. (Right) Suspended replica bone balance scale with flax strings and leather pouches, holding replica weights 99 and 23 in equilibrium.

ACKNOWLEDGMENTS. We thank Francesco Carrer, Andrea Dolfini, Rachel Crellin, Joseph Maran, Matthew Knight, Carl Knappett, Andrea di Renzoni, Giancarlo Lago, Michele Ortolani, and Maja Gori for their precious comments and critiques. We are grateful to the anonymous reviewers, whose comments greatly helped improve this paper. The research in this article was supported by the European Research Council and by the University of Rome

“La Sapienza.” The European Research Council funded the research under the European Union’s Horizon 2020 Framework Programme and was carried out within the scope of the ERC-2014-CoG “WEIGHTANDVALUE: Weight metrology and its economic and social impact on Bronze Age Europe, West and South Asia,” based at the Georg-August-Universität of Göttingen, Germany (Grant 648055), Principal Investigator: Lorenz Rahmstorf.

1. C. Renfrew, “Systems of value among material things: The nexus of fungibility and measure” in *The Construction of Value in the Ancient World*, J. K. Papadopoulos, G. Urton, Eds. (Cotsen Institute of Archaeology Press, 2012), pp. 249–260.
2. C. Pare, “Weighing, commodification, and money” in *Oxford Handbook of the European Bronze Age*, H. Fokkens, A. Harding, Eds. (Oxford University Press, 2013), pp. 508–527.
3. A. Mederos, C. C. Lamberg-Karlovsky, “Converting currencies in the old world. *Nature* 411, 437 (2001).
4. J. Pakkanen, “Aegean Bronze Age weights, chaîne opératoire and the detecting of patterns through statistical analyses” in *Tracing Prehistoric Social Networks through Technology: A Diachronic Perspective on the Aegean*, A. Brysbaert, Ed. (Routledge, 2011), pp. 143–166.
5. W. B. Hafford, “Weighing in Mesopotamia. The balance pan weights from Ur. *Akkadica* 133, 21–65 (2012).
6. K. M. Petruso, *Ayia Irini. The Balance Weights: An Analysis of Weight Measurement in Prehistoric Crete and the Cycladic Islands*. *Keos VIII* (Philipp von Zabern, 1992).
7. M. A. Powell, “Masse und Gewichte” in *Reallexikon der Assyriologie und Vorderasiatischen Archäologie* 7, D. O. Edzard, Ed. (de Gruyter, 1987), pp. 457–530.
8. A. Archi, “Reflections on the system of weights from Ebla” in *Eblaïtica: Essays on the Ebla Archives and Eblaïtic Language*, C. H. Gordon, G. A. Rendsburg, N. H. Winter, Eds. (Eisenbrauns, 1987), vol. 1, pp. 47–83.
9. J. G. Dercksen, “Money in the old Assyrian period” in *Merchants, Measures and Money. Understanding Technologies of Early Trade in a Comparative Perspective*, L. Rahmstorf, G. Barjamovic, N. Ialongo, Eds. (Wachholtz Verlag, 2021), pp. 331–359.
10. P. Steinkeller, “Towards a definition of private economic activity in third millennium Babylonia” in *Commerce and Monetary Systems in the Ancient World*, R. Rollinger, C. Ulf, Eds. (Franz Steiner, 2004), pp. 91–112.
11. V. Bartash, *Establishing Value: Weight Measures in Early Mesopotamia. Studies in Ancient Near Eastern Records* 23 (De Gruyter, 2019).
12. W. Helck, “Maße und Gewichte” in *Lexikon der Ägyptologie* III, W. Helck, E. Otto, W. Westendorf, Eds. (Harrassowitz, 1980), pp. 1199–1214.
13. D. R. Frayne, *The Royal Inscriptions of Mesopotamia. Early Periods* (University of Toronto Press, 1997).
14. C. Wilcke, “Der Codex Urnamma (CU): Versuch einer Rekonstruktion” in *Riches Hidden in Secret Places. Ancient Near Eastern Studies in Memory of T. Jacobsen*, T. Abusch, Ed. (Eisenbrauns, 2002), pp. 191–233.
15. G. Barjamovic, “Technologies of trade in western Asia in the Middle Bronze Age” in *Merchants, Measures and Money. Understanding Technologies of Early Trade in a Comparative Perspective*, L. Rahmstorf, G. Barjamovic, N. Ialongo, Eds. (Wachholtz Verlag, 2021), pp. 55–67.
16. F. Joannès, “Les méthodes de pesée à Mari. *Rev. Assyriol. Archeol. Orient.* 83, 113–152 (1989).
17. K. Kristiansen, “The rise of bronze Age peripheries and the expansion of international trade 1950–1100 BC” in *Trade and Civilisation. Economic Networks and Cultural Ties, from Prehistory to the Early Modern Era*, K. Kristiansen, Ed. (Cambridge University Press, 2018), pp. 87–112.
18. H. Vandkilde, “Bronze Age beginnings—A scalar view from the global outskirts. *Proc. Prehist. Soc.* 85, 1–27 (2019).
19. T. Wilkinson, *Tying the Threads of Eurasia. Trans-regional Routes and Material Flows in Transcaucasia, Eastern Anatolia and West Central Asia, c. 3000–1500 BC* (Sidestone, 2014).
20. T. Earle, J. Ling, C. Uhnér, Z. Stos-Gale, L. Melheim, “The political economy and metal trade in bronze Age Europe: Understanding regional variability in terms of comparative advantages and articulations. *Eur. J. Archaeol.* 18, 633–657 (2015).
21. R. Englund, “Equivalency values and the command economy of the Ur III period in Mesopotamia” in *The Construction of Value in the Ancient World*, J. K. Papadopoulos, G. Urton, Eds. (Cotsen Institute of Archaeology Press, 2012), pp. 427–458.
22. D. K. Foley, “A statistical equilibrium theory of markets. *J. Econ. Theory* 62, 321–345 (1994).
23. F. A. Hayek, “The use of knowledge in society. *Am. Econ. Rev.* 35, 519–530 (1945).
24. H. Mollat, “Zur Metrologie der Gewichtstücke Alt-Ägyptens. *Maß und Gewicht* 84, 2045–2077 (2007).
25. P. Delougaz, *The Temple Oval at Khafajah* (Oriental Institute, 1940).
26. B. Horejs, “Neue Gewichtssysteme und metallurgischer Aufschwung im frühen 3. Jahrtausend—ein Zufall?” in *Von Baden bis Troia—Ressourcennutzung, Metallurgie und Wissenstransfer. Eine Festschrift für Ernst Pernicka. Oriental and European Archaeology* 3, M. Bartelheim, B. Horejs, R. Krauß, Eds. (Leidorf, 2016), pp. 251–272.
27. L. Rahmstorf, “Emerging economic complexity in the Aegean and Western Anatolia during the earlier third millennium BC” in *Of Odysseys and Oddities. Scales and Modes of Interaction between Prehistoric Aegean Societies and Their Neighbours*, B. P. C. Molloy, Ed. (Oxbow Books, 2016), pp. 225–276.
28. E. Ascalone, L. Peyronel, *I pesi da bilancia dell’età del Bronzo Antico e Medio. Materiali e Studi Archeologici di Ebla* 7 (Sapienza, 2006).
29. A. Vacca, “The Tuqan IC pottery sequence from area P South” in *Tell Tuqan Excavations and Regional Perspectives. Cultural Developments in Inner Syria from the Early Bronze Age to the Persian/Hellenistic Period*, F. Baffi, R. Fiorentino, L. Peyronel, Eds. (Congedo Editore, 2014), pp. 45–84.
30. L. Rahmstorf, “Weight metrology in the Harappan civilization” in *South Asian Archaeology and Art 2014*, E. Myrdal, Ed. (Dev, 2020), pp. 77–96.
31. K. Frielt, *The island of Umm An-Nar* (Jutland Archaeological Society Publications, 1995), vol. 2.
32. E. Ascalone, “Pesi dall’Iran orientale” in *Tales of Three Worlds. Archaeology and Beyond: Asia, Italy, Africa*, D. Usai, S. Tuzzato, M. Vidale, Eds. (Archaeopress, 2020), pp. 3–16.

33. N. Ialongo, The earliest balance weights in the West: Towards an independent metrology for bronze Age Europe. *Camb. Archaeol. J.* **29**, 103–124 (2019).
34. A. Cardarelli, M. Pacciarelli, P. Pallante, "Pesi e bilance nell'età del Bronzo italiana: quadro generale e nuovi dati" in *Archaeological Methods and Approaches: Industry and Commerce in Ancient Italy. British Archaeological Reports International Series 1262*, E. De Sena, H. Dessales, Eds. (Archaeopress, 2004), pp. 80–88.
35. C. Pare, "Weights and weighing in Bronze Age Central Europe" in *Eliten in Der Bronzezeit: Ergebnisse Zweier Kolloquien in Mainz Und Athen. RGZM Monographien 43* (Römisch-Germanisches Zentralmuseum, 1999), pp. 421–514.
36. L. Rahmstorf, Scales, weights and weight-regulated artefacts in Middle and Late Bronze Age Britain. *Antiquity* **93**, 1197–1210 (2019).
37. R. Vilaça, "Ponderais do bronze final-ferro inicial do ocidente peninsular: Novos dados e questões em aberto" in *Barter, Money and Coinage in the Ancient Mediterranean (10th–1st Centuries BC). Anejos de Archivo Español de Arqueología 58*, M. A. Paz García-Bellido, L. Callegarin, A. Jiménez, Eds. (Instituto de Historia, 2011), pp. 139–167.
38. N. Ialongo, L. Rahmstorf, "The identification of balance weights in pre-literate Bronze Age Europe: Typology, chronology, distribution and metrology" in *Weights and Marketplaces from the Bronze Age to the Early Modern Period. Proceedings of Two Workshops Funded by the European Research Council (ERC)*, L. Rahmstorf, E. Stratford, Eds. (Wachholtz Verlag, 2019), pp. 106–126.
39. M. A. Powell, "Ancient Mesopotamian weight metrology: Methods, problems and perspectives" in *Studies in Honour of Tom B. Jones. Alter Orient Und Altes Testament 203*, M. A. Powell, R. H. Sack, Eds. (Butzon & Bercker, 1979), pp. 71–109.
40. N. Parise, Mina di Ugarit, mina di Karkemish, mina di Khatti. *Dialoghi di Archeol.* **3**, 155–160 (1981).
41. A. S. Hemmy, "System of weights" in *Further Excavations at Mohenj-Daro*, E. J. Mackay, Ed. (Government of India, 1938), pp. 601–612.
42. W. Kula, *Measures and Men* (Princeton University Press, 1986).
43. M. A. Powell, Money in Mesopotamia. *J. Econ. Soc. Hist. Orient* **39**, 224–242 (1996).
44. N. Ialongo, G. Lago, A small change revolution. Weight systems and the emergence of the first Pan-European money. *J. Archaeol. Sci.* **129**, 105379 (2021).
45. W. B. Hafford, Mesopotamian mensuration: Balance pan weights from Nippur. *J. Econ. Soc. Hist. Orient* **48**, 345–387 (2005).
46. D. D'Arnaud, Y. Calvet, J.-L. Huot, Ilišu-Ibnišu orfèvre de l'E.BABBAR de Larsa, la jarre L. 76-77 et son contenu. *Syria* **56**, 1–64 (1979).
47. F. B. Kulakoğlu, "Balance stone weights and scale-pans from Kültepe-Kanesh: On one of the basic elements of the old assyrian trading system" in *Overturning Certainties in Near Eastern Archaeology. Festschrift in Honor of K. Aslihan Yener*, M. Çiğdem, M. T. Horowitz, A. S. Gilbert, Eds. (Brill, 2017), pp. 341–402.
48. M.-P. Hendrickx-Baudot, The weights of the Harappa-culture. *Orient. Lovan. Period.* **3**, 5–34 (1972).
49. C. Pulak, "The balance weights from the Late Bronze Age shipwreck at Uluburun" in *Metals Make the World Go Round. The Supply and Circulation of Metals in Bronze Age Europe. Proceedings of a Conference Held at University of Birmingham in June 1997*, C. Pare, Ed. (Oxbow Books, 2000), pp. 247–266.
50. F. Petrie, *Glass Stamps and Weights. Ancient Weights and Measures* (University College, 1926).
51. M. A. Cour-Marty, "Les poids inscrits de l'Ancien Empire" in *Études Sur l'Ancien Empire et La Nécropole de Saqqâra*, C. Berger, B. Mathieu, Eds. (Université Paul Valéry, 1997), pp. 129–145.
52. D. B. Kendall, Hunting quanta. *Philos. Trans. R. Soc. Lond. A* **276**, 231–266 (1974).
53. R. Hermann, J. Steinhoff, P. Schlotzhauer, P. Vana, Breaking news! Making and testing Bronze Age balance scales. *J. Archaeol. Sci. Rep.* **32**, 102444 (2020).
54. H. Altenmüller, Ist die Waage im Gleichgewicht? Noch einmal zu den Wiegesenen des Alten Reiches. *Göttinger Miszellen* **89**, 7–14 (1987).
55. K. P. Kuhlmann, Gewicht" und die Redewendung jw. F m jnr „im Gewicht sein". *Göttinger Miszellen* **22**, 39–41 (1976).
56. T. Pommerening, *Die altägyptischen Hohlmaße. Studien zur Altägyptischen Kultur, Beihefte*, **10** (Helmut Buske Verlag, 2005).