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Communicated by Jürgen Renn

Received November 6, 2015
Revised November 15, 2016
Accepted November 30, 2016
Published April 4, 2017

Edited by Gerd Graßhoff and Michael Meyer, Excellence Cluster Topoi, Berlin

eTopoi ISSN 2192-2608
http://journal.topoi.org

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The paper uses a new research tool, the *Digital Atlas of Innovations* to re-think the invention and diffusion of wheeled vehicles in Eurasia during the 4th and 3rd millennium BC. It is argued that the diffusion of wheeled vehicles is the result of the local transformation of several technical components which have been known since the Pottery Neolithic. The technical knowledge to combine these components was widely spread and resulted in experimentation with the use of animal traction already in the late 6th millennium. It were, however, the significantly better connected networks which were established during the early 4th millennium, which enabled the innovation-diffusion of the wheel from its presumed zone of origin in the Black Sea area to the Baltic. The same technology (minus the wheels) is also adopted in many other regions, where it is transformed according to local specifications (ploughs, sleds).

Technical innovation; diffusion of innovations; Neolithic; Bronze Age; wheel and wagon; ploughing; cattle traction.


Technische Innovation; Diffusion von Innovationen; Neolithikum; Bronzezeit; Rad und Wagen; Pflug; tierische Zugkraft.

1 Introduction

Maps have become a central part of modern information economies. While the illustrative appeal of traditional maps is widely acknowledged, new digital maps based on extensive and dynamic databases also offer new prospects for science.

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Within the Excellence Cluster Topoi, area D6 is working on the Digital Atlas of Innovations (Fig. 1). The Digital Atlas of Innovations is a new research tool that can map repartitions of artifact types, styles, and techniques. The Atlas also includes a research program where the results of scientific discussions are turned into interactive and interoperable maps, which in themselves are a tool to ask new questions. The maps not only allow for an enhanced visualization of scientific problems, but also offer a novel heuristic approach that enables researchers to reconceptualize these problems and work on new solutions. This paper will demonstrate the use of the Digital Atlas of Innovations by studying the development of wheeled vehicles in the 4th and 3rd millennium BC.

2 Early wagons as an example of paradigmatic shifts in prehistory

Traditional narratives of prehistory were based on diffusionist paradigms heavily influenced by Gabriel Tarde, who was himself influenced by the archaeological debate of his time. In the works of Oscar Montelius, Sophus Müller, V. Gordon Childe, and others, change was the result of the successive adaption of innovations that had originated in a core area, in the surrounding peripheries.

The chain-dating of objects from these ‘peripheries’ via typological analogies with sites dated by written sources, however, was easily vulnerable to errors: historical chronologies in the Near East and Egypt began around 3000 BC, such that wrong dates for older cultures were an inherent consequence of the dating system. Most regions outside the Near East lacked sites with multiple layers deposited upon each other (so-called tell settlements) and thus a control of the proposed chronology by stratigraphical means was impossible. Therefore the result of the analysis (diffusion) was also its methodological means, and this could easily lead to circular logic.

With the advent of large-scale radiocarbon records, the traditional diffusionistic relationships between Central Europe and Western Asia have become significantly more difficult to uphold. Chronology was liberated from typological chain-dating, and this resulted in earlier dates for key technologies in the periphery. Since then, narratives about the European Neolithic often stress the cultural autochthony or the possibility of an evolution independent from the Orient. The discussion of early wagons closely follows this rough outline: whereas older models were based on an ex oriente perspective, the radiocarbon revolution has caused a dramatic reevaluation of the known evidence, which has resulted in a lively and controversial discussion on the date and place of the origin of wheeled vehicles.

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2 For more details concerning research group D-6, cf. [https://www.topoi.org/group/d-6](https://www.topoi.org/group/d-6) (visited on 17/02/2017). Data entry for this study was assisted by Luisa Gerlach, B.A., Kyra Gospodar, B.A. and Friederike Jürke, B.A.

3 E.g. [http://www.topoi.org/event/26293](http://www.topoi.org/event/26293); [http://www.topoi.org/event/26387](http://www.topoi.org/event/26387); [http://www.topoi.org/event/31052](http://www.topoi.org/event/31052); [https://www.topoi.org/event/33098](https://www.topoi.org/event/33098) (all visited on 17/02/2017).


7 E.g. Todorova 1981; Radiovojvč and Rehren 2016.

8 E.g. Burmeister 2004a.

9 E.g. Childe 1931; Childe 1944; Sherratt 1983; Sherratt 1985; Sherratt 1986.

The wheel is considered one of the most important technical innovations in prehistory. The traditional model was invented in the Near East. From there, it was thought to have been transmitted to Europe during the 3rd millennium.\textsuperscript{11} New discoveries and new radiocarbon dates of known finds have changed this picture dramatically. The current understanding of the distribution of wheeled vehicles between 3500 and 3000 BC spans the area from the North Sea to the Euphrates, and dating difficulties have made it impossible to determine the oldest evidence of wheeled vehicles.\textsuperscript{12}

Some recent developments have changed the picture even more from the traditional model. High-precision dating of the megalithic grave of Flintbek LA3 in northern Germany corrected the age of the wagon traces under the grave slightly, to 3460–3385 BC,\textsuperscript{13} while the earliest Near Eastern evidence has been considerably altered. Not only have the depictions on the tablets from Uruk been challenged as to whether they actually depict wagons,\textsuperscript{14} but this view has also been strengthened by the new data from the ARCANE project, which makes clear that the earliest models of wheels did not appear until around 3100 BC.\textsuperscript{15} That, in turn, would make the invention of wheeled vehicles in Mesopotamia less probable.

Nevertheless, it seems rash to conclude an autochthonous evolution of wheeled vehicles in northern Germany from this new evidence. Not only is the chronological dis-
discussion far from finished, but it is also misleading and anachronistic to see ‘Europe’ and ‘the Orient’ as closed units inside which intercultural contacts are taken for granted, even as connections between both regions are usually doubted. Such a perspective needs to take into account the radically different state of research, for instance in Anatolia, Syria-Mesopotamia and Iran, as well as the cultural filters, region-specific adaptations, and local technical traditions. The results from prehistoric excavations in Upper Mesopotamia highlight that the time span in question is still largely unknown. As a consequence, most scholars still agree that either a very quick diffusion or a stimulus diffusion remain better explanations.

3 Defining the data set: Wheeled Vehicles vs. Animal Traction

The following text is based on the data set Evidence for Animal Traction, with the last update on 24 April 2015. The collection of this data set and the idea of mapping it came out of extensive discussion and classification.

The available evidence of early wheeled vehicles cannot be summed up easily within the typological repertoire used to deal with archaeological finds, and consequently the archaeological discourse is often blurred by the mixing of several groups of finds, different categories of evidence, and debatable interpretations on the same level.

Evidence of early wagons might come from areas as diverse as wagon graves, pictographs on clay tablets, depictions on rock art, miniature discs interpreted as wheels, wagon-shaped drinking vessels, archaeological features thought to be track-marks of wagons, i.e. the preserved imprints created by the wheels of a wagon that was driving over soil, etc. This already very heterogeneous body of evidence is complemented by indirect proofs that modern interpreters think might be related to the wagon. The depiction of two cattle under a yoke, double cattle-burials, roads constructed to be wide enough to allow wagons to drive on them, and even spindle whorls have been brought forward in this respect.

With very few exceptions, there are no complete prehistoric wagons, with the archaeological record preserving only parts of the wagon or the draft animals in a variety of archaeological sources. The pieces of evidence themselves are often not very clear either. They may be shortened or stylistically abstracted, as well as damaged, incomplete, or badly preserved, and their interpretations may vary significantly as a consequence: in the Central European scientific discourse, depictions of two cattle under a yoke are often interpreted

16 Nevertheless, Prüs also acknowledges the value of the Uruk evidence as earlier (Prüs 2011, 244), and the recent reevaluation of the southern Levantine chronology suggests that the problem might be much more difficult, e.g., Lebeau’s linking of EJZ 5 with the beginning of the Early Bronze Age II in Palestine (i.e., around 3100–2900 BC, cf. Regev, Miroshedji, Greenberg, et al. 2012; Regev, Miroshedji, and Boaretto 2013).

17 Oates et al. 2007.

18 Cf., inter alia, Burmeister 2002; Bakker et al. 1999.


21 Johanssen and Laursen 2016.

22 Burmeister 2002.

as evidence of wagons, whereas similar evidence is seen as a pars pro toto for plowing in Near Eastern archaeology. The ambiguity of the data, however, also stems from the technology itself. Wagons consist of a pair of cattle, a chassis, and wheels on an axle. It was not necessary to use all components of this package simultaneously all the time, but single components could be isolated for different tasks; for instance, the cattle pair was also able to pull a plow or heavy objects. Because of the blurry nature of the archaeological record, it is possible that evidence of such ‘secondary’ tasks might have been preserved without any evidence of the ‘complete’ wagon.

Previous analyses have also failed to cope with that complexity by only focusing on the wheeled vehicles themselves, ignoring their modular character: Wagons consist of several components developed and working independently from one another: wheels on an axle, a wooden chassis, and two animals trained to pull the vehicle. Components of this system can be extracted and reinvented (or ‘developed’) in different social and technical contexts. Yet these components may still be reintroduced into the technical system thereafter, or even a reinvented version thereof. This paper takes the most complicated module from the technical system ‘wagon’ to understand it, namely the pair of cattle trained to move at the same pace. The necessary woodworking skills and extensive knowledge of rotary motion can be assumed to have been present since the Pottery Neolithic, but while domestic cattle were also widely known from the Neolithic onwards, their use for pulling vehicles or plows is not clear.

I will argue, therefore, that it is the development of cattle traction that is decisive for the start of the innovation process. Toward this end, a data set comprising many types of evidence for the existence of cattle traction has been compiled (with the assumption that wheels in any case require animals to pull them).

The data set consists of 4,914 finds of more or less significant evidence for the use of traction that are described and classified in several categories. This includes wheeled vehicles or parts thereof, wagon figurines and miniature wheels, wheeled drinking cups, cattle burials, depictions of cattle pairs, depictions of wagons, drivable roads (i.e., with a width of more than 200 centimeters), unwheeled vehicles (like sleds and travois), plows, plow marks and tread marks, yokes, and evidence of pathological deformations on skeletons of cattle caused by heavy labor and surcharge of the bones. Only finds securely dated to the 3rd millennium or earlier are analyzed here, ignoring the large group of petroglyphs from Eurasia that have been very difficult to date.

The finds were described in several categories, including general geographical and descriptive attributes (like length, width, material, registration number, etc.), as well as the dating method; the archaeological context (grave, hoard, settlement, single find, etc.); the type of evidence (real-life objects, pictures, models, imitations/skeuomorphs, archaeological features, skeletal evidence, and textual evidence); the number, diameter, thickness and type of the wheels; the gauge of the wheels; and the number and type of draft animals. Additionally, the finds were loosely grouped together according to their evidential and archaeological quality (bone deformation, cattle burial, drivable road, wagon figurine, miniature wheel, pictograph, plane surface art depicting a wagon, plastic pottery decoration, plow marks, pottery decoration, seal depiction, siege equipment, unwheeled vehicles, wagon or wagon part, wheeled animal figurine, wheeled ceramic vessel, wheel tread.

24 E.g. Matuschik; Bakker 2004, 284.
26 For instance, the drilled perforations on axes (Brandt 1967, 14–19) and use of spindle-whorls (Grömer, Hofmann-de Keijzer, and Rösel-Mautendorfer 2016).
27 Benecke 2004; Boroffka 2004.
28 Novozhenov 2012.
marks, and yoke). The dating of the finds was discussed for every item individually, with radiocarbon dating taking priority over nonscientific dates. For the finds from western Asia, the ARCANE chronology\(^29\) was used. It should be mentioned that this paper will not discuss every characteristic of this database in detail; instead, some features will be selected that are thought to be relevant for the scientific discourse.

4 Using an intellectual atlas to understand prehistoric wagons

The Digital Atlas of Innovations includes software that is able to plot queries from an attached archaeological database on a map and thereby calculate the rate of adoption and present it as a histogram. The time span, the geographical area, and the units of the histogram can all be freely defined and presented as pie charts with the user-defined criteria from the database. All elements are interconnected and thereby allow the diffusion processes to be analyzed in real time and the underlying data to be critically challenged.

While maps are frequently used to depict research results in archaeology, the Digital Atlas of Innovations allows archaeological maps to be deployed as heuristic tools to apprehend the diffusion of artifacts, knowledge, or social phenomena through time and space.

In this paper, I will demonstrate how a large set of nonuniform data can be tackled using the Digital Atlas of Innovations. My initial aim is to demonstrate the specifications of the data and make a meaningful selection for the question of the emergence of the wagon and its diffusion.

5 Evidence of early wagons in Eurasia

As a first step, all available data is selected and plotted. This makes a very broad perspective necessary involving Eurasia and North Africa. A first general overview of the mapped data, i.e., all finds relating to cattle traction until the end of the 3rd millennium, highlights several major concentrations: one huge cluster on the Indian subcontinent, another two large clusters in the Near East and Scandinavia, and smaller concentrations around the Black Sea region and in central Europe (Fig. 2).

It is striking that huge blank areas still appear on the map. Animal traction was not used in western Europe, Greece, northern Scandinavia, or North Africa – with the exception of Egypt and large parts of Eurasia – for as long as 1,500 years after the first appearance of the wagon.

The evidence is not divided evenly over all find groups, but the majority (ca. 71.3 percent) of finds are wagon figurines and miniature wheels, while only 14.5 percent belong to real-life wagons and cattle burials. The models and miniatures of wagons primarily derive from settlements; their main centers are Upper Mesopotamia and the northwestern part of the Indian subcontinent, with a number of scattered finds through central Europe. The majority of these finds date to relatively late within the sequence of early evidence for wagons (ca. 2600–1800 BC) (Fig. 3). Real-life evidence, on the other hand, is mostly found in graves and has its peak from 3300 to 2500 BC, with a strong concentration around the Black Sea (Fig. 4).

The interactivity of the Digital Atlas provides further decoding of the picture. The huge amount of figurines can be identified as mainly belonging to the Harappa culture, dating to ca. 2600–1800 BC. The social innovation of making small model carts is therefore responsible for the significant concentration in India and Pakistan, but not

\(^29\) http://www.arcane.uni-tuebingen.de/database/ (visited on 17/02/2017).
Fig. 2 | Repartition of evidence for the use of animal traction before 2000 BC.

Fig. 3 | Repartition and adoption rate of ‘models and miniatures’ giving evidence for animal traction in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

necessarily for a similar more intensive use of real-life wagons (see Fig. 3). Selecting the finds from Harappa itself demonstrates that the over 3,000 finds from this site alone are also responsible for the peak in the dating frequency of the figurines in general (Fig. 5).
In the same way, wagons or parts thereof form a heavy concentration in the area north of the Black Sea, and the main source of cattle burials can be identified as southern Scandinavia, where a large group of barrow graves (so-called stone-heap graves) are commonly interpreted as cattle burials (Fig. 6).

While there is some slight overlapping of these three find groups, there is not only a different chronological sequence, but also a surprisingly regional consistency visible, both
of which call for further exploration. Therefore, the same data set will now be mapped according to the archaeological contexts and evidence types.

The vast majority of finds come from settlements (79.4 percent), mostly from the aforementioned three distinct centers of wagon figurines (Harappa, Upper Mesopotamia, and central Europe) (Fig. 7).

A smaller amount were placed in graves (15.8 percent), with concentrations in northern Germany, the Low Countries, and Jutland on the one hand, and the northern and
eastern Black Sea area on the other (Fig. 8). Unknown sources accounted for 3.4 percent, while the rest were either found as single finds, near prehistoric roads, or in a scant few hoards (Fig. 9). It is striking that the evidence from graves is significantly older than that from settlements, beginning as early as 3500 BC.

While the wagon-model group is almost completely responsible for all the settlement finds (97.4 percent) – again with a high concentration in the Harappa culture (see Fig. 8) – the real-life wagons are strangely absent in exactly that region. An explanation for this can be seen in the high correlation between graves and real-life objects: 79.2 percent of
real-life wagon evidence was found in funerary contexts, and this, in turn, corresponds with the aforementioned concentrations of finds in the Pontic area and on the Cimbrian Peninsula (Fig. 10).

The skeletal evidence (4.5 percent) is also mainly distributed in the latter region and derives from graves (Fig. 11), which correlates mostly with cattle burials, since it is difficult to identify single bones from settlement layers as being from cattle used for traction. The low number of skeletal evidence finds in comparison to the other groups, however,
makes it difficult to compare the frequency. The Digital Atlas of Innovation allows users to change the depiction of frequencies from absolute to relative or logarithmic scales. Changing the frequency to percentages highlights that skeletal evidence is rather short-lived (Fig. 12) and that its dating correlates with the date for cattle pairs in general (see Fig. 6).

The few wheeled drinking cups are limited to the Baden culture and usually found in graves (Fig. 13). The marks from plows, sleds, or wheels (1.9 percent), meanwhile, are...
bound to the existence of barrows, which explains their limitation to England, Jutland, and northern Germany, or wet soils. This makes dating the marks rather difficult, and in most cases only a *terminus ante quem* can be given. Based on the available dating evidence, it is possible that plowing was used in the North European Plain as early as shortly after 4000 BC (Fig. 14).

Depictions (2.3 percent), on the other hand, have a fairly widespread repartition; they are known from Megalithic graves, for instance the Wartberg group of southern
Westphalia and Hesse,\textsuperscript{30} and as rock art, for instance in the Alps\textsuperscript{31} as well as Eastern Anatolia,\textsuperscript{32} Mesopotamia, and Iran\textsuperscript{33} (Fig. 15). There are also a significant number of finds in Central Asia.\textsuperscript{34} Many of these finds, however, are difficult or even impossible to date, or date to later than the European finds, and also include pictographs, rock art, and wall paintings and carvings.

While the majority of finds considered evidence of early wagons come from the Harappa settlements, these finds consist only of model wagons, dating rather late (see Fig. 5). The knowledge of the use of animal traction in western Eurasia is heavily biased by the cultural decision to put parts of wagons or models thereof into graves or to decorate graves with wagon depictions, and even further by the choice of how to build graves: tread marks from plows and wagons had a significantly better chance of preservation in places where barrows were constructed over the deceased. Additionally, the soil conditions work as a natural filter for the archaeological record, and roads and real-life parts of wagons as well as skeletal evidence only survive outside graves that are located within regions with wet soils.

Early evidence of animal traction can thus be shown to be first and foremost the result of ritual actions by prehistoric communities. Region-specific deposition patterns are visible: the rich evidence in Jutland, northern Germany, and the Low Countries is not only due to the bogs, but also a result of the construction of graves in which cattle bones were preserved and the erection of barrows, under which marks from plowing and driving could survive the millennia. In central Europe, the evidence consists of a few depictions from Megalithic graves, double burials of cattle and wheeled pots found in a small number of graves, while in the northern Pontic region a vast number of wagons (this time, however, without cattle) were preserved in graves. Had prehistoric communities not chosen to build such graves, the amount of evidence would be significantly lower and more ambiguous.

The impact of prehistoric cultural choices for the preservation of finds is not only relevant in order to understand the representativity of the archaeological record, but also to grasp the rhythm of the innovation process: only 5.9 percent of all finds can be connected with a radiocarbon dating (Fig. 16). The repartition of these, however, is again strongly biased: while only 32 percent of all graves are scientifically dated (Fig. 17), 80.2 percent of all radiocarbon-dated finds derive from graves, and another 4.5 percent from roads (Fig. 16). This means that datings independent from typology are more or less congruent with the repartition of the evidence from graves and wet soil (where the wagon parts and parts of the skeleton can survive and appear in the archaeological record; cf. Fig. 18). An overwhelming amount of miniature wagons and miniature wheels can still only be dated by means of stratigraphy, however, often with a lack of connected scientific date (Fig. 19).

The aforementioned possible chronological priority of Europe should therefore be treated with great care. It is based on a record that is strongly filtered by cultural choices and natural conditions, and cannot simply be seen as giving objective evidence of diffusion gradients.

\textsuperscript{30} Günther 1993.
\textsuperscript{31} Vosteen 1996b, 44.
\textsuperscript{32} Есин, Ю. Н. 2012, 41, Abb. 21.
\textsuperscript{33} J. Crouwel 2004, 69, 77 Abb. 15.
\textsuperscript{34} Teufer 2012.
Fig. 16 | Repartition and contexts of C14-dated evidence for animal traction found in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

Fig. 17 | Repartition and dating methods of evidence for animal traction found graves in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).
Fig. 18 | Repartition and dating methods of skeletal evidence for animal traction in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

Fig. 19 | Repartition and dating methods of miniatures and models, interpreted as evidence for animal traction in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).
6 The takeoff of the wagon reconsidered

Scholars have identified the 4th millennium as the time span in question for the emergence of the wagon, or more precisely the time from the middle of the 4th until the first quarter of the 3rd millennium. If only finds from this period are mapped, a histogram of the finds shows a rapid increase in the 34th century BC (see Fig. 7). This would allow the diffusion to be connected with the well-known S-curve from innovation theory, which is meant to describe a successful innovation process: within a given time frame, the number of users slowly rises until a critical mass is reached, which causes further diffusion to commence much faster and resemble a cascade. Rogers calls this phase the ‘take-off’.

But does the histogram in question indeed show the prehistoric reality, or are the cultural and natural filters discussed above blurring the picture to an extent that it is impossible to converge on the takeoff of the wagon using empirical data? I will try to discuss this further by disassembling the data into smaller units and comparing the preliminary result of an assumed takeoff with other data sets.

7 Rotary motion

As has been shown, the strong correlation between prehistoric religious actions and science-based dating hinders the understanding of the innovation process. A better understanding of the technical principles of traction and wheeled vehicles is needed.

One plausible idea would be to see the wagon as the result of a better understanding of rotary motion. And indeed, within the time frame of interest, the second half of the 4th millennium, several changes in the archaeological record have been connected with such a notion: in Swiss lake dwellings there is a dramatic rise in the number of spindle whorls that coincides with the beginning of the Horgen culture; also appearing within this period are the fast-turning potter’s wheel, the cylinder seal, and doors rotating around door-socket stones. There seems to be a connection between spinning and the appearance of linen in the Circum-Alpine area, but a further correlation with a localized invention of wagons simplifies the underlying technical principles. Spinning and spindle whorls are already very prominent in the 5th millennium in the southern Levant and on the Lower Danube.  

Fig. 20 | Frequency of finds of evidence for animal traction (orange), cylinder seals (purple) and potter’s wheels (green) in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

35 Rogers 2003.
38 Levy and Gilead 2012.
Fig. 21 | Repartition and frequency of finds of evidence for animal traction (orange), cylinder seals (purple) and potter’s wheels (green) in the 4th millennium BC.

Nevertheless, while a comparison of the relative frequency of wheeled vehicles with the data sets ‘potter’s wheels’ and ‘cylinder seals’ suggests that all three are independent innovation processes with different takeoffs within the 2nd half of the 4th millennium (Fig. 22), it also highlights that all three share a possible earliest beginning around 3600 BC. If the scope is narrowed to the 4th millennium only, it becomes clear that the specific takeoffs take place between 3300 and 3100 BC, with a clear priority of traction over cylinder seals and potter’s wheels (Fig. 22). The corresponding mapping remains peculiar, however, because now the evidence for wheeled vehicles is concentrated only
in Europe, and the evidence for the potter’s wheels and cylinder seals is limited to the eastern Mediterranean (Fig. 22).

8 Regionally exclusive and time-specific find groups

It could also be argued that the ritual veneration of wagons, which resulted in the making of miniatures and the inclusion of these miniatures in burials, was the result of their great popularity after their emergence. To test this hypothesis, the dating and repartition of smaller classificatory units will be plotted.

The early evidence for animal traction does indeed appear in find groups specific to certain regions and time: in the Hessian-Westphalian region, it shows up as pecked depictions on the wall stone slabs of the Wartberg Culture; in Flintbek, as tracks under a burial mound of the late Funnelbeaker culture; in Poland, as depictions on Funnelbeaker pots and as cast copper sculptures; in the area of the Baden and Cotofeni cultures, as models; in the northern Pontic region, as grave goods; in the lakeside settlements of the Circum-Alpine region and the bogs of northwestern Germany and the Netherlands, as realia finds; and, finally, in the Cucuteni-Trypillian culture, as animal figurines on wheels.

The repartition changes slightly if only the timespan until 2750 BC is selected, but its find frequency is different, as the thousands of models from Harappa are omitted (Fig. 23).

This selection is used to create a new data set for the next mapping (Fig. 24):

The spatial exclusivity of the find groups mentioned has already been demonstrated, but it has remained unclear how these groups compared chronologically. Of course, with many of these categories, like the Funnelbeaker pots or the Wartberg megaliths, not only is the find number statistically irrelevant, but the absolute chronology is also heavily interdependent. This significantly limits the detailed chronological comparison of all find groups in a discussion that focuses only on single finds. With some of the larger, more generally distributed groups, however, there are some interesting tendencies visible, especially when using big data to argue the point: real-life wagons and wagon parts rapidly increase from around 3500 BC onwards (Fig. 25), while cattle burials are a bit later and do not have their takeoff until ca. 3100 BC; roads that could be used by wagons (see Fig. 6) are known from at least 4000 BC onwards, but have a significant increase around 3150 BC (Fig. 26). The ritual appreciations of cattle, as well as the construction of roads specifically designed for driving wagons, seem to have been the consequence of more widespread vehicle use.

40 Günther 1995
41 Zich 1992
42 Kruk and Milisauskas 1982; Kruk and Milisauskas 1991; Milisauskas, Kruk, and Poliszot-Makowicz 1993
43 Bakker 2004, 284 Fig. 2.
44 Maran 2004, 271 Fig. 2–4, 272 Fig. 5–6; Burmeister 2011, 225 Fig. 23.
45 Trifonov 2004.
Fig. 23 | Selection process for evidence for animal traction in the 4th millennium BC (query from the Digital Atlas of Innovations).

Fig. 24 | Repartition of evidence for animal traction in the 4th millennium BC (query from the Digital Atlas of Innovations).
Fig. 25 | Repartition and frequency of real-life-sized evidence for animal traction in the 4th millennium BC (query from the Digital Atlas of Innovations).

Fig. 26 | Repartition and frequency of drivable roads in the 4th millennium BC (query from the Digital Atlas of Innovations).
9 Local technical developments

The aforementioned exclusivity of the find groups greatly limits the comparison of the technical details of early wagons. The only objects that do appear in greater number are wheels.

Disc wheels made from one (Fig. 30), two (Fig. 31), or three parts (Fig. 32) are not limited to a specific area; rather, all basic principles of wheel construction seem to have been shared over the complete central and western area of the repartition of early evidence (in the case of the Harappa culture, this cannot be decided on the basis of miniatures alone).

Using additional construction details, it is possible to sketch different technical traditions. In the 4th millennium, four-wheeled wagons are restricted to Poland, the Carpathian Basin, the Caucasus, and Syria-Mesopotamia; their find numbers drastically increase from around 2750 BC onwards (Fig. 27). Light two-wheeled carts, on the other hand, are found only in the Wartberg Culture, possibly central Germany, and the western Alpine region, and these carts continue in great numbers in the Near East during the 3rd millennium (Fig. 28). If it is accepted that these are transformations of the same basic principle, as discussed further above, then they must represent a rather late stage of the diffusion, in which the wheeled vehicle as a technological system has already been further developed into at least two constructional variants.

The elaborate design of early wagons also highlights the difficulty of seeing any experimentation phase. For instance, the wheels from Stare Gmajne in Ljubljana, Slovenia belong to a small group of disc wheels with square-shaped center bores limited to southern central Europe (Fig. 29). The wheels are fixed on the axle and thus cause less abrasion, suggesting that they are already at a more developed stage of the innovation process.

Fig. 27 | Repartition and relative frequency of evidence for four-wheeled vehicles in the 4th and 3rd millennia (query from the Digital Atlas of Innovations).

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49 Friedrich and Hoffmann 2013.
50 Pétrequin et al. 2002, 62 Fig. 9.
51 Velušiček 2002, 39 Fig. 2, 40 Fig. 3; Fansa 2004, 34 Fig. 41, however, the find is mistakingly placed into Czechia.
Fig. 28 | Repartition and relative frequency of evidence for two-wheeled vehicles in the 4th and 3rd millennia (query from the Digital Atlas of Innovations).

Fig. 29 | Repartition and relative frequency of evidence for wheels with a square-shaped centre-bore in the 4th and 3rd millennia (query from the Digital Atlas of Innovations).
Fig. 30 | Repartition and relative frequency of single-piece disc-wheels in the 4th and 3rd millennia (query from the Digital Atlas of Innovations).

Fig. 31 | Repartition and relative frequency of bipartite disc-wheels in the 4th and 3rd millennia (query from the Digital Atlas of Innovations).
Cattle pairs and the wagon

The wagon is rarely shown (or preserved) completely in archaeological sources. The scientific community has agreed to read various depictions as a *pars pro toto* sign for 'wheeled vehicle.' This is quite clear in the case of wagon drinking cups, but when dealing with pairs of cattle (sometimes under a yoke), other possibilities remain.

Nevertheless, even if the cipher of two cattle could also refer to cattle pulling a plow, or a sled or travois, any of these readings would require animal traction, and it is hardly by coincidence that the traction of a cattle pair is used as a signifier. Between 3300 and 2800 BC, the cattle pair can be found depicted in megalithic graves of the Wartberg group in Hesse-Westphalia, as rock art in the Val Camonica and the Black Sea region, as cattle burials near stone heap graves on the Jutland Peninsula and within the Bernburg and Baden cultures, as copper figurines, and as protomes or small figurines attached to pots in eastern central Europe (Fig. 33).

With the exception of Jutland, contemporary evidence for wheeled vehicles exists in all these areas, so the reading of the cattle pair under a yoke as a wagon is possible. The same image is also found on a small bowl in Tell el-Farah (North) in the southern Levant dating to the older part of the Early Bronze Age, as well as on a seal from Arslantepe and a stone relief from southern Mesopotamia. Thus, while the use of animal traction is

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52 Cf. the excellent overviews in: Fansa and Burmeister, 2004.
54 Inter alia: Schlichterle, 2004, 311 Fig. 18; Piggott, 1985, 52 Fig. 21; cf. also: Arcà, 2011.
55 Günter, 1993, 53 Fig. 9.
57 Döhle and Stahlhofen, 1985, 157–159 Fig. 1; Stahlhofen and Kurzhals, 1983, 157–160; Vosteen, 1996, 48.
59 Matuschik, 2003; cf. also Bakker, 2004, 284 Fig. 2; Matuschik, 2006, Fig. 8.1.
60 Radosina and Boglarelle, Bondár, 1992, Fig. 7.3a–c; Bondár, 2012, Fig. 7–8. – Krežnica: Dinu, 1981.
61 Dayagi-Mendels and Rozenberg, 2010, 39 Fig. 4.
62 Fansa, 2004, 15 Fig. 9.
63 Fansa, 2004, 17 Fig. 12.
well known, the evidence for constructing wheeled vehicles is rather sparse, and in Egypt even nonexistent.

10.1 Early indirect evidence

Interestingly, evidence that precedes the appearance of real-life objects can be found for the use of animal traction in both rock art (starting around 3850 BC, Fig. 34) and figurines. A possibly similar phenomenon can be seen for evidence of the wheel, where a group of wheeled figurines in the Tripylia culture\(^6\) (Fig. 35) and some miniature wheels in the Carpathian Basin\(^5\) (Fig. 36) date to as early as the first half of the 4th millennium.

The depictions thus predate the real-life evidence by up to 500 years. How can this chronological discrepancy be explained? It could be taken as an argument to further strengthen the proposed interpretation of the general adoption curve as showing a cultural innovation rather than a technical one, or it might suggest flaws within the current interpretation of the archaeological record. The previously explained taphonomic factors are one option, but it is important at this stage of the argument to consider the different technical complexity of the components again. Human societies since at least the Neolithic have had knowledge of the necessary woodworking tools, the principle of rotary motion, the idea of vehicle movement, and the concept of animals pulling heavier objects.

\(^6\) Guiev 1998
\(^5\) Burmeister 2011, 225 Fig. 23.
Fig. 34 | Repartition and frequency of plane surface art showing animal traction in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

Fig. 35 | Repartition and frequency of wheeled animal figurines in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).
10.2 The use of cattle traction

Recall also that seemingly isolated early evidence was available inside the group of drivable roads as well (see Fig. 8). Furthermore, the recent find of a yoke dating to the Cardial culture suggests some early experimentation with cattle traction, and cattle castration (which could be related to this) was indeed practiced beginning in the Early Pottery Neolithic. The available data on cattle pathologies shows that from the Pottery Neolithic onwards, there is evidence in the Near East of cattle regularly pulling heavy weights.

The repartition stretches from Scandinavia to the Levant (Fig. 38), and the evidence of skeletal pathologies is considerably older than the evidence of traction, beginning as early as the 7th millennium. If the selection is limited to the 4th millennium, there is a parallel increase around 3350 BC in both curves (Fig. 39), suggesting a connection between the two phenomena.

The area can also narrowed to central Europe by making a geographical selection with the Atlas of Innovation software (Fig. 40).

If this narrowing is performed, both adoption rates are nearly parallel (Fig. 41). This phenomenon is also reflected in the evidence of plowing in Europe. While plow treads are notoriously difficult to date, there is a plausible terminus post quem of 4000 BC (Fig. 42). The correlation of tread marks, cattle-pair depictions, and zooarchaeological evidence is striking and highlights that animal traction, plowing, and the wheel were very probably introduced into northern central Europe as a package.

Rogers defined five criteria for the successful takeoff of an innovation: the relative advantage over other technologies, the compatibility with the social system, the complexity of the innovation, its individual trialability, and its observability. An innovation has to be perceived as being better or more prestigious than traditional techniques (relative advantage, compatibility, complexity, trialability, observability).
advantage); it has to be consistent with existing values and experiences of the society adopting it (compatibility); and it has to be understood, i.e., its complexity must not be too high.

Once prehistoric wagons had emerged, they could be observed by anyone living in the vicinity of a user. While these vehicles were significantly less mobile than the later chariots, their advantages in societies based on agriculture are obvious: they allowed the transport of heavier objects and the moving or shifting of objects with less effort. The main innovation aspects deserving more attention here are the criteria of compatibility and complexity.
Fig. 39 | Repartition and frequency of pathologies from traction on cattle skeleton in the 4th millennium BC (query from the Digital Atlas of Innovations).

Fig. 40 | Repartition of pathologies from traction on cattle skeleton in Central Europe in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).
Fig. 41 | Geographical selection process and repartition and frequency of pathologies from traction on cattle skeleton in Central Europe in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).

Fig. 42 | Repartition and frequency of ploughing marks in the 4th and 3rd millennia BC (query from the Digital Atlas of Innovations).
Wagons seem to have been incompatible with many societies, who either saw no use at all for them or decided that other ways to transport goods were better. The lengthy refusal to adopt the wheel in Greece\(^{70}\) and Egypt\(^{71}\) is striking; wheeled vehicles were obviously not the only choice for transportation. The record of wagon evidence is not continuous in the Near East, either, and there are several periods in which the evidence seems to disappear.\(^{72}\)

The complexity of wagon technology was relatively low; it should have been easy for most Neolithic communities to build these simple machines. Rotary motion (see above) was well known and did not ‘push’ or enable wagon technology. Rather, the development went the opposite way, insofar as the knowledge of wagons inspired new applications for rolling objects and pivoting axes.

The technical know-how required to construct a chassis was certainly less complex than that necessary for constructing a wooden longhouse (which Neolithic societies began doing in the 6th millennium). One could, nevertheless, argue that the construction of wheels might have caused some difficulties. The introduction of hollow copper chisels has been brought forward as a direct prerequisite for the making of wheels,\(^{73}\) mainly because of the association of two chisels in Ebla with a donkey and a wagon, dated around 2850 BC. In southeastern Europe, hollow chisels are known from finds in Brono-Lišen,\(^{74}\) Fajz in Transdanubia,\(^{75}\) and Petralona,\(^{76}\) as well as one at Tell Dipis near Ezero, Bulgaria in a layer set into the late 3rd millennium because of analogies with Troy III-V.\(^{77}\) Even if the chronological discrepancy makes clear that such chisels cannot be connected with the invention of the wheel, they might be partially responsible for its takeoff.\(^{78}\) It is remarkable that neither the Early Neolithic cultures of Central Europe nor the early Funnelbeaker culture seems to have produced flint chisels, and that in these regions, chisels appear later towards the end of the 4th millennium BC.\(^{79}\)

The necessary knowledge to construct vehicles, to use animals to pull these vehicles, and to understand a pivoting axle was available between Central Europe and Mesopotamia in the 4th millennium BC, but did not result in the diffusion of a uniformly designed cart. Instead, combinations of the single components were included in local technical systems.

Stefan Burmeister has remarked that the different technologies suggest that the idea and not the artifact was transferred,\(^{80}\) but I think it is possible to specify this even more: the available know-how was used to produce objects that the socio-technical substructure of the given societies could support, and these were adapted to the local environment. For instance, in the Alpine region, wagons with an A-shaped chassis are thought to derive

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\(^{70}\) The oldest evidence is still the model from Palaikastro, dating to the early 2nd millennium BC. Couwel 1981: Taf. 49, 752.

\(^{71}\) The oldest find dates from the late 3rd millennium. Cf. Quibell and Hayter 1927 frontispiece; also shown: Burmeister 2004b, 23.

\(^{72}\) E.g., in the Middle Euphrates region wagon models do not appear before the Early Middle Euphrat 3 period, i.e., 2747/2625–2525/2492 cal BC; cf. Pruß 2015; Deckers, Drechsler, and Sconzo 2015, 420 Fig. 14.

\(^{73}\) Piggott 1983, 25.

\(^{74}\) Hansen 2009a.


\(^{76}\) Hansen 2013, 162.

\(^{77}\) Klimscha 2010, 114 Fig. 7.

\(^{78}\) Hansen 2013, 162. Simpler, flat chisels nevertheless happen to be found in earlier contexts, for instance at Arslantepe, dating to c. 3800–3400 BC (Frangipane et al. 2003), and at Tall Hujayrat al-Ghuzlan, near Aqaba, Jordan, dating to 3650–3500 BC (Klimscha 2014).

\(^{79}\) Brandt 1967, 109–126.

\(^{80}\) Burmeister 2004a.
from the A-shaped travois\textsuperscript{81} from Reute-Schorrenried\textsuperscript{82} and Chalain,\textsuperscript{83} or the rock art from the Val de Fontalbe in Mont Bego.\textsuperscript{84}

With very few and ambiguous examples left outside, however, the evidence of the use of animal traction in cattle pairs correlates well with the overall innovation process of wheeled vehicles. Therefore, I would argue, the takeoff of wagons is the result of the wider availability of animal traction and, to a lesser degree, a better understanding of the economic usages of rotary motion, as well as the production of specialized woodworking tools. Vast areas of Eurasia were aware of the use of animal traction, but this knowledge led to very distinct solutions visible in the archaeological record because it still had to be translated into local technical and ritual traditions. The \textit{chaine opératoire} was simple enough to be moved between societies with grossly varying social complexity, and it could build upon technical knowledge that was widely known. Once established in a number of communities, the innovation could be scrutinized and easily transformed according to the requirements of different environments and social rules. The takeoff was remarkably quick, and within some 300 years cattle-drawn vehicles and plows were being brought into many areas between the North Sea and the Black Sea. The prerequisite for such a rapid takeoff should be a correspondingly high communication density within this area in the time preceding adoption.

11 Modeling the innovation process of the wheel and the wagon

The aim of this paper has been to highlight a \textit{longue-durée} perspective on the innovation process of the wagon, using the interoperable maps of the Digital Atlas of Innovation. The technical principles necessary to build wheeled vehicles were known since the Neolithic Revolution, and the knowledge of even explicit technical modules like the pivoting axle and the use of cattle to pull heavy objects was present significantly earlier than the takeoff period of the wagon.

12 Conclusion: The secondary products revolution rethought

The foregoing has established a connection between the technical evolution of the wagon and the circulation of know-how within a larger sphere of interaction, with the knowledge of traction as the major factor. This sphere can be defined independently by the repartition of pottery styles, lithic technocomplexes, or copper artifacts. It is constructed from several smaller interaction zones that may also have included the exchange of human resources. The technical know-how circulating within these zones was then transformed according to local specifications.

A successive intensification of communication frequency and quality during the 4th millennium can be demonstrated, and its peak correlates with the takeoff of the wagon in western Eurasia, when evidence for animal traction and the wheel can be seen between the Persian Gulf, the Alps, the North Sea, and the Caucasus. Suddenly societies of grossly differing complexity (ranging from early states to egalitarian villages) seem to recombine their available know-how to produce wheeled vehicles. The analysis of the maps in this paper makes a monocentral diffusion very unlikely – even for stimulus diffusion. When the available knowledge is widely available and already being continuously transformed,

\textsuperscript{81} Schlichterle \textit{ibid.}, 26.

\textsuperscript{82} Mainberger \textit{ibid.}, Fig. 8.

\textsuperscript{83} Pétrequin et al. \textit{ibid.} 6c Fig. 6–7.

\textsuperscript{84} Pétrequin et al. \textit{ibid.} 62 Fig. 9; Arcà \textit{ibid.} 74 Fig. 2; cf. also the extensive catalogue of Lumeley \textit{ibid.}.
it is more plausible to assume a more active role for all the participants in the networks within the discussed sphere of interaction.

I do not want to propose multiple inventions, but instead to stress the polynodal infrastructure of the sphere of interaction. Such a network is not only continuously exchanging information, but also transforming it in the process. There is no single node emitting ‘the’ idea; rather, sets of ideas travel together with artifacts and people. This is how technical know-how is accumulated, and with techniques as simple as the wagon, the underlying idea can be used as a template to create region-specific technical solutions. The different ways that animal traction was used – the two-wheeled carts of the Alpine region, the cattle-drawn sleds in the Near East, or the four-wheeled wagons in the Pontic area – can be understood as interpretations of this template. All deploy the combination of traction and vehicle, and optionally (!) the wheel.

Stages of the innovation process of wheeled vehicles might therefore have taken place in different contexts and only for selected components of the technical system. Although some regions chose to construct different meanings for the innovation, this did not exclude them from adopting the original meaning at a later stage. The relative simple chaîne opératoire of wheeled vehicles allowed societies to quickly transform any development stage thereof to fit with locally reinvented components. A good example of this is the introduction of the battle cart as depicted on the Standard of Ur, which integrated a new form of traction that was originally developed in a completely different context. Other examples include the integration of the domestic donkey into the technical system and the development in the Alps of wagons and travois with an A-shaped chassis.

Indeed, the wheel is the least important part of this technical set. In Egypt, the Levant, and Syria-Mesopotamia, the set is used only rarely for vehicles. Nevertheless, the socio-technical relations within these societies make use of the principle in a multitude of ways: doors rotating on a door socket, cylinder seals, and the potter’s wheel, for instance.

For a final look from a broader perspective, all data entries were classified according to whether they were evidence for vehicle movement, animal traction, or the wheel. Both the idea of vehicle movement by animal traction (Fig. 43) and the wide adoption of the wheel (Fig. 44) correlate fairly well and seem to be closely connected.

What was the impulse responsible for the wagon’s takeoff? As I have shown, the technical components later used for the wagon were already in existence in earlier times, and as Burmeister has recently argued, it is very possible that the actual invention of the wagon could have happened as early as the 5th millennium. The evidence for the use of animal labor clearly favors such a view. Nevertheless, the widespread appearance of wheeled vehicles and the plow between the North Sea and the Euphrates is a striking novelty only in the late 4th millennium BC, and seem to confirm Andrew Sherratt’s concept of a Secondary Products Revolution.

This paper has shown that, for some parts of Europe, there is strong evidence that the visibility of the wagon is closely connected with its introduction, while for other parts of Eurasia, ideological changes are responsible for the evidence appearing in the archaeological record.

Thus, two lines of thought converge:

Either wagon technology could arrive as a package (traction + plow + wheel), or the necessary technical knowledge was already available. In both cases, the emergence of the

85 Littauer and J. H. Crouwel loc. cit. 36 Fig. 1
86 Pétrequin et al. loc. cit. 60 Fig. 6–7.
87 Burmeister loc. cit.
88 Hill loc. cit.
89 Sherratt [1984].
wagon resulted in experimentation with previously known technology and a variety of usages.

The archaeological evidence highlights many changes that might be connected with the intensified use of animal traction. Raising megalithic graves would definitely have been much easier using animal traction, and the context of the wagon tread marks at Flintbek clearly suggests the use of vehicles at some point during the construction. This intensification might have resulted in a dependency on such animal technology, and this, in turn, would explain the social innovations of using wagons in funeral rites. By this point, animal traction and the wheel would have become part of socioeconomic systems.

Yet this was not the end, but the start of new innovation processes connected with other innovations: in the Near East, for instance, the combination of wagon technology,
the domestication of the donkey,90 and specialized close-combat weapons91 was integral to the construction of the first battle carts and the transformation of warfare.

These manifold changes were not caused by the wagon, of course, but the wagon was one part of a larger process that radically transformed Eurasia during the 4th millennium: the industry of heavy copper weapons and tools in the Balkans and the Carpathian Basin ceased to exist,92 as did the production of clay figurines93, while writing, sealing, balance systems94 as well as the domestic donkey95 appeared – but only in the eastern Mediterranean.

Contact and small-scale change did not stop at the end of the 4th millennium. On the contrary, within the time span from 3500 to 2200 BC, it is difficult to clearly see periods without innovations – it is only from a modern, etic perspective that innovations like animal traction, wheels, and plowing are valued higher than halberds,96 flanged copper axes,97 Baniabic-type axes,98 or stone stelae.99

The implementation of key innovations like animal traction, the plow, and the wheel did have great long-term consequences, however, as Peter Bogucki has shown:100 social units that were able to monopolize the control of such innovations were able to accumulate food, wealth, and possibly also political power. The subsequent transition from the Funnelbeaker ideology to the Corded Ware is connected with a shift from technical to social innovation, and it might therefore be another worthy adventure to closely analyze the long-term effects of technical change in the 3rd millennium in a similar manner.

Illustration credits

1 DAI/Eurasien-Abteilung und Max-Planck-Institut für Wissenschaftsgeschichte.

91 Klimscha 2014.
92 Schubert 1966.
93 Hansen 2009a.
95 Cf. Milevski 2011, 185–186 Fig. 10.3 Fig 10.4; Klimscha 2013, 99–102.
97 Klimscha 2010.
98 Hansen 2011.
99 Vierzig (unpublished).
100 Bogucki 1993.
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