Speeding up. Prehistoric animal traction and the revolute joint

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Abstract

The use of animal in draft, particularly cattle, is likely as old as their domestication. However, due to high friction between sledges and sleighs and the ground or high work input implied by roller bearings, Neolithic and Copper Age animal traction was likely rather slow. Here, the revolute joint, an innovation of the late fourth and the early third millennia BCE, brought about wheelsets and wheels for carts and wagons along with other applications such as pivoted doors, the potter's wheel, and levers. As first automotoric machines in human history, wheelset and wheeled vehicles increased the work speed of draught cattle significantly and helped to shift prehistoric economies from being labour-limited to land-limited. Moreover, they enabled the use of horses as draught animals for Bronze Age chariots and Roman travel carts, resulting in an increase in travel speed. In terms of acceleration, these innovations were as significant as the acceleration period we currently encounter that started with industrialization.

Résumé

L'utilisation de la traction animale, en particulier les bovins, est probablement aussi ancienne que leur domestication. Cependant, en raison du frottement élevé entre les traîneaux et le sol ou de la charge de travail importante impliquée par les roulements à rouleaux, la traction animale du Néolithique et de l'Âge du Cuivre était probablement plutôt lente. Ici, l'articulation tournante, une innovation de la fin du quatrième et du début du troisième millénaire avant notre ère, a donné naissance aux essieux et aux roues des charrettes et des chariots, ainsi qu'à d'autres applications telles que les portes pivotantes, le tour du potier et les leviers. En tant que premières machines automotrices de l'histoire de l'humanité, les véhicules à ensembles de roues ou à roues ont considérablement augmenté la vitesse de travail des animaux de trait et ont contribué à faire passer les économies préhistoriques d'une situation où la main-d'œuvre était limitée à une situation où la terre était limitée. En outre, ils ont déclenché l'utilisation de chevaux comme animaux de trait pour les chars de l'Âge du Bronze et les voitures de voyage romaines, ce qui constitue une étape dans la réduction du temps de voyage dans la préhistoire. Ces innovations ont probablement été aussi importantes que la période d'accélération que nous connaissons actuellement et qui a débuté avec l'industrialisation.

Kurzfassung

Die Nutzung der Zugkraft von Tieren, insbesondere von Rindern, ist wahrscheinlich so alt wie ihre Domestikation. Aufgrund der hohen Reibung zwischen Schlitten und Boden oder des hohen Arbeitsaufwands, den Rollenlager mit sich bringen, ging die Zugtiernutzung im Neolithikum und in der Kupferzeit jedoch bestenfalls eher langsam vonstatten. Das Rotationsgelenk, eine Erfindung des späten vierten und frühen dritten Jahrtausends v. u. Z., führte zu Radsätzen und Rädern für Karren und Wagen sowie zu anderen Anwendungen wie Schwenktüren, der Töpferscheibe und Hebeln. Als erste automotorische Maschinen in der Geschichte der Menschheit steigerten Gefährte mit Radsätzen oder Rädern die Arbeitsgeschwindigkeit von Zugtieren erheblich und trugen dazu bei, dass die prähistorische Wirtschaft nicht mehr durch die verfügbare Arbeitskraft, sondern v.a. durch die verfügbaren Landflächen begrenzt war. Darüber hinaus lösten Radsatz und Rad die Verwendung von Pferden als Zugtiere für bronzezeitliche Streitwagen und römische Reisewagen als weiteren Beschleunigungssprung in der Vorgeschichte aus. Was die Beschleunigung anbetrifft, waren diese Innovationen wahrscheinlich ebenso bedeutsam wie jene, die seit der Industrialisierung die Beschleunigungsphase auslösten, die wir bis heute erleben.

Resumen

El uso de animales en el campo del cultivo, especialmente del ganado, es probablemente tan antiguo como su domesticación. Sin embargo, debido a la elevada fricción de los trineos o incluso el gran esfuerzo que suponían los rodamientos contra el suelo, la tracción animal en el Neolítico y la Edad de Cobre era probablemente bastante lenta. Es debido a esto que la innovadora pieza de ingeniera de finales del cuarto y principios del tercer milenio a.C. de la unta, trajo consigo numerosos juegos de ruedas tanto para carros y carretas, además de otras aplicaciones como puertas pivotantes, torno de alfarero y las palancas. Como primeras máquinas automotrices de la historia de la humanidad, los vehículos aumentaron considerablemente la velocidad de trabajo del ganado de tiro y contribuyeron a descentrar las economías prehistóricas limitadas a mano de obra con terrenos reducidos. En consecuencia, el uso de caballos como animal de tiro para carros se popularizó en la Edad de Bronce, reduciendo así los tiempo de trayecto. Estas innovaciones provocaron un periodo de aceleración, el cual se asemeja al proceso iniciado en la revolución Industrial, que continua desarrollándose exponencialmente hasta la actualidad.

Animal traction in prehistoric archaeology

Animal traction as a secondary product

Andrew Sherratt in 1981 put forward the idea that in the Neolithic and Chalcolithic, animals were only exploited for their primary products – products obtained by slaughtering an animal, such as meat, leather, and bone. Secondary products, i.e. products that can be "harvested" from living animals, such as milk, maybe blood, and wool as well as workforce, in contrast, were only exploited from the turn from the fourth to the third millennium BCE onwards, which marks – in broad terms - the turn to the Bronze Age. Further research into this topic over the last decades, however, has considerably reshaped this idea[1]. Rather than a "Secondary Products Revolution", the time around 3000 BCE is now perceived as a phase of rapid intensification of much older incipient secondary product use[2].

While wool production requires a particular genetic mutation in sheep that is currently assumed to have indeed happened in later prehistory[3], increasing evidence points to a Neolithic onset of animal milk and traction use. According to osteological hints, milking might be as early as the domestication of sheep, goat and cattle, and biochemical evidence demonstrates that milk was regularly processed in ceramic vessels from the seventh millennium BCE onwards[4]. Moreover, there is now increasing material evidence also for the Neolithic use of animal traction. From the late fourth millennium BCE onwards, however, evidence for animal traction use not only gets much more frequent, but also includes new species such as donkeys and horses. Admittedly, part of this increase in finds is a function of changed cultural practices and, hence, preservation conditions; but since this is true mainly for Europe, the situation in South-west Asia suggests that also animal traction witnessed an intensification from the fourth millennium BCE onwards.

Archaeological sources for animal traction

Except for northern latitudes where acidic soils prevent their preservation, animal bones are among the most frequent finds in most archaeological sites. Among the animal species traditionally used in traction, the dog is the oldest domesticate, as wolf husbandry started among later Palaeolithic hunters and gatherers from ca. 30000 BCE onwards[5]. Cattle were domesticated together with sheep and goat from ca. 9000 BCE onwards when farming developed in the early Neolithic after the end of the last ice age. Donkey and horses, however, were domesticated several thousand years later around 3000 BCE at the transition from the Neolithic or Chalcolithic to the Bronze Age[6]. Camels followed around 1000 BCE[7], and for the onset of reindeer domestication a wide date range between ca. 1500 BCE and 800 AD is debated[8].

However, as the presence of species potentially suited for traction work does not mean they were actually used in traction, zooarchaeologists look for signs of wear and tear on the bones: cattle traction use has been demonstrated to result in broadened surfaces in the distal phalangeal joints judging from a sample of slaughtered modern traction animals from rural Romania[9] and is a trait that can be distinguished also in archaeological material. In horses, in addition, bridling can lead to bit wear visible on the teeth in archaeological material[10].

Wood, bone and leather as the traditional materials for the manufacture of traction gear hardly survive in the archaeological record, so actual finds are limited to permafrost, arid or waterlogged conditions that are found in regions that have been settled later in the course of prehistory due to their adverse climatic conditions. The same is true for wooden road tracks built in marshy land. With the onset of the metal ages, highly strained construction parts such as bridles and wagon hubs have been increasingly replaced by metal, which can then be found in the archaeological record. However, the assumed high degree of metal recycling limits such finds mainly to grave goods in rich burials that may not always reflect standard work equipment but rather elitist items. Moreover, sledges and wagons as well as ards can leave traces in soft ground. However, such traces quickly erode unless they are buried under soil soon after, limiting their preservation to time periods when burial mounds were common.

Prequel: Mesolithic and Neolithic

Wooden runners found in Vis I in modern Russia dated to the seventh or sixth millennium BCE[11] suggested that Mesolithic hunter-gatherers used skis and sledges (**Figure 1**). While we cannot yet say for sure if humans or dogs pulled such vehicles[12], it is likely that contemporary Neolithic communities further south knew about sledges and travois-like devices, too, although interpretation of a wooden fragment from the Cardial site of La Draga (Banyoles, Espagne) in the 6th millennium BCE is questionable[13]. Hauling sledges is not only possible on snow cover or frozen ground, but also on dry soil if the load is not too heavy. Additionally, grass cover can lower friction considerably[14], similar to how threshing sledges traditionally used in arid regions like South-west Asia glide over cereal and pulse straw No actual prehistoric threshing sledge has survived, but at e. g. sixth millennium BCE Çatalhöyük West, squarish flint blades bearing a gloss characteristic for cutting plant material have been found[15]. Their resemblance to known insets into later prehistoric threshing sledges is so striking that a Neolithic use of threshing sledges should at the moment not be entirely excluded[16]. First ard marks and actual ard finds, in contrast, are only attested from ca. 3000 BCE onwards and – together with archaeobotanical evidence[17] – suggest that

1 Sherratt 1981.
2 Greenfield 2010.
3 Benecke et al. 2017.
4 Evershed et al. 2008; Hendy et al. 2018.
5 Bergström et al. 2020.
6 Librado et al. 2021.
7 Orlando 2016.
8 Pelletier et al. 2020.
9 D e Cupere et al. 2000
10 Greenfield et al. 2018.
11 Burov 1981.
12 Sinding et al. 2020.
13 Guilaine 2003, 147.
14 Atkinson 1956, 109.
15 Rosenstock et al. 2019a, 178.
16 Ostaptchouk 2016, 101, 119p; Kamjan et al. 2022.
17 Bogaard 2004, id. 2005.

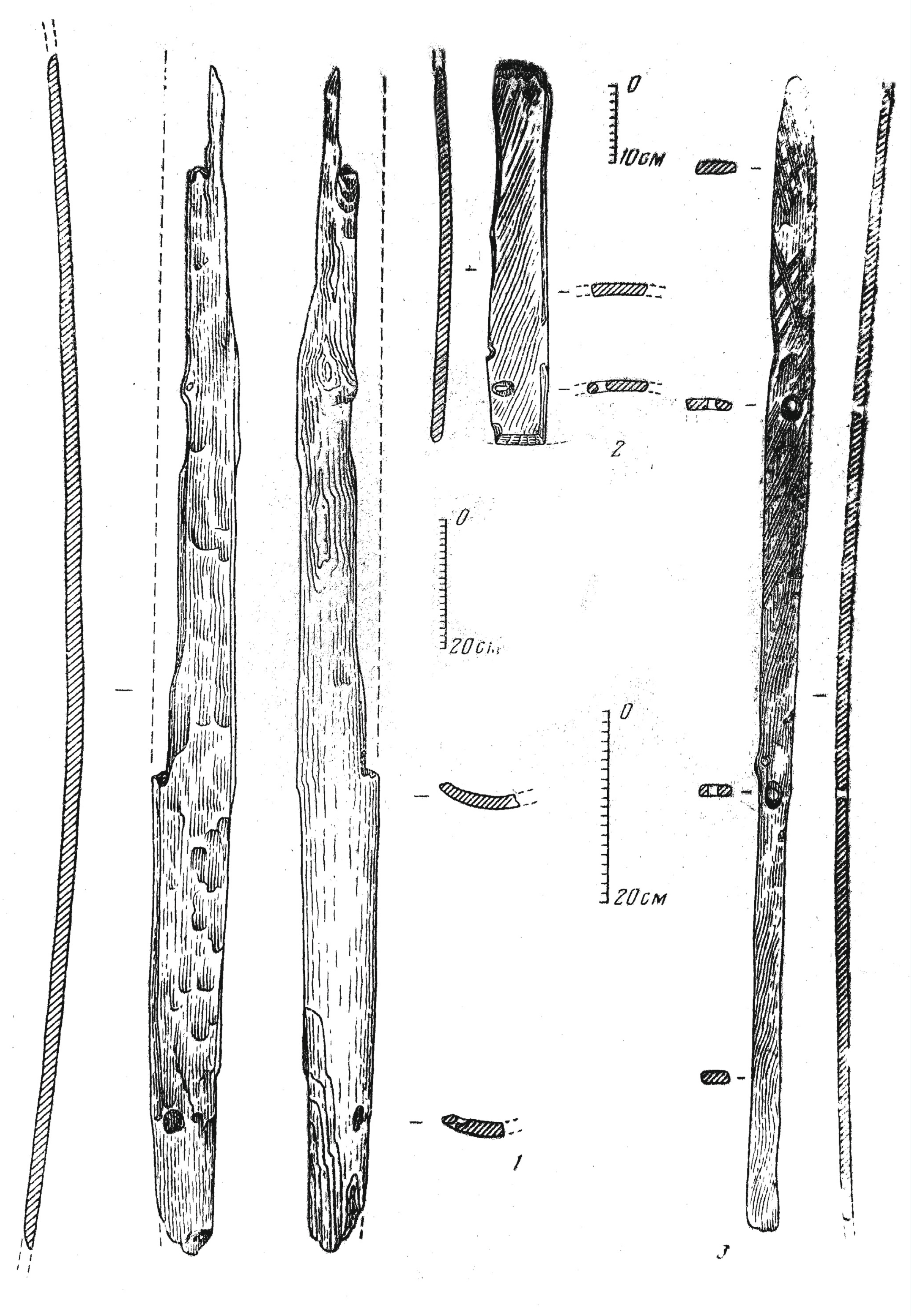

Figure 1 – 7th or sixth millennium BCE sledge runners or skis from Mesolithic Vis

Neolithic agriculture was hoe-based. However, this can only hold true if the absence of evidence for the ard is not only caused by preservation biases. Especially in the European Neolithic, when primeval forests had to be cleared to obtain agricultural land and timber-framed architecture, cattle draught force might have been welcome also for logging, a practice known today, too[18].

While all this merely hints at the possibility of early draught cattle, bones with broadened distal phalangeal joint surfaces observed at Early Neolithic sites in South-eastern Europe (***Figure 2***) confirm that cattle were at least occasionally used in draft tasks already in the Neolithic[19]. Such "ad hoc draft use" still – like milking – requires some training and hence a certain degree of familiarity between animals and humans. This demonstrates that people and their herds lived close together despite the lack of evidence for penning or even stabling of cattle close to the settlements in the Neolithic[20].

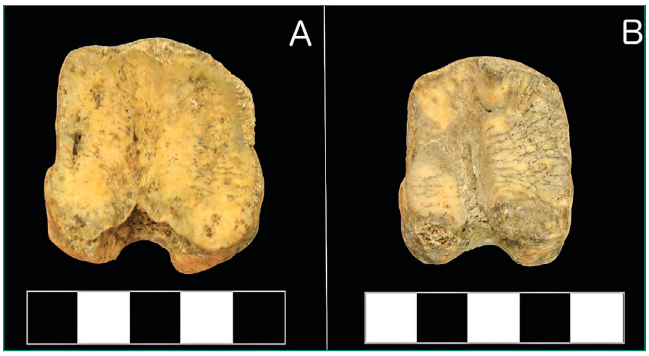

Figure 2 *– Broadened proximal articular surfaces of Bos taurus anterior second phalange from Foeni-Salaş (A) pointing to traction use in comparison to a specimen with the usual dimensions from Blagotin (B), both ca. 6000 BCE*

Chalcolithic and Early Bronze Age ca. 4000 – 2000 BCE

Ards and sledges

First evidence for ards is only known from around 3000 BCE onwards. Unlike later ploughs, ards do not turn the soil and do not distribute it on the field, but merely create furrows. Hence, fields of the Copper and Bronze Ages were ploughed in a criss-cross fashion. The soil under the mound of Jordehøj in Denmark dating from 3500 to 3300 BC has preserved one of the earliest examples of ard marks. Judging from rock carvings at Bagnolo and Borno 1 in Val Camonica/Italy probably also dating to the 2nd half of the 4th millennium BCE, ards were pulled by cattle teams of two[21]. The first preserved actual ards (***Figure 3***) such as the one from Walle near Aurich in Lower Saxony, Germany, however, date to the early 2nd millennium BCE[22] and are as simple wooden constructions as those observed in recent traditional contexts.

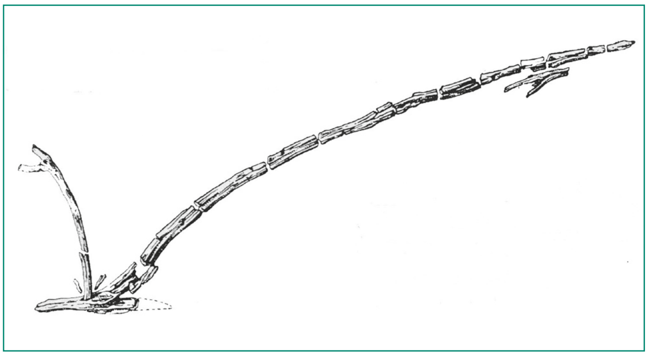

Figure 3 *– One of the first preserved ards from Walle – initially dated to the 3rd, now redated to the early 2nd millennium BCE*

Cylinder seals of the late Uruk period (ca. 3500-3100 BCE) of Mesopotamia, such as from Arslantepe (near Malatya, Turkey), show sledges with one seated person and another one standing on the sledge or next to it and controlling the single draught animal using a spike and a rein (***Figure 4***). The details of the harnessing are somewhat unclear, but the high friction of a sledge renders drawbars that enable the animal to brake the vehicle downhill unnecessary at least in flat terrain, so the connection between the animal's horn and the sledge shown likely represents some sort of traces. Remains of a sledge or wagon from the Early Dynastic period (ca. 2750-2350 BCE) and the skeletons of two bovids have been recovered from tomb RT 800 of the royal cemetery at Ur (Iraq)[23]. Details of the construction, including the attachment of the draught pole, however, remain unknown. Biblical passages such as 2 Kings 13:7, "For there was no more left of the people of Jehoahaz than fifty horsemen, ten chariots and ten thousand footmen. For the king of Syria had slain them, and made them as the dust of the threshing", could explain such sledges as symbolic attributes of high-ranking individuals derived from the threshing sledge. Threshing sledges are archaeologically attested by so-called Canaanite blades interpreted as lithic insets from the fourth millennium BCE onwards[24] and are traditional devices in arid regions like Southwest Asia.

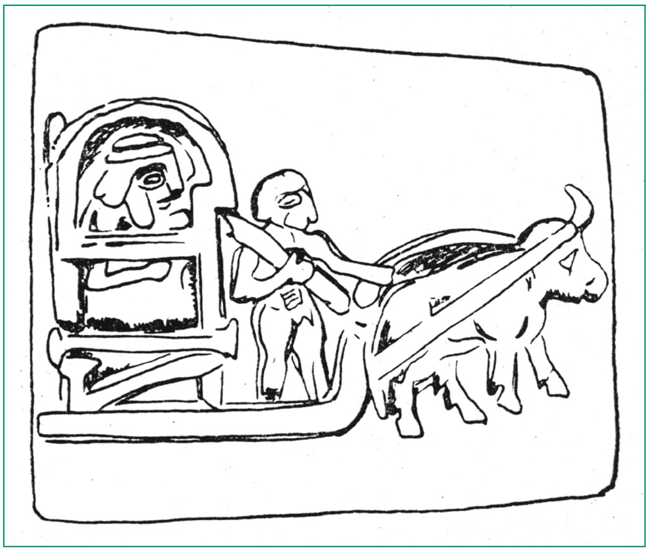

Figure 4 *– Late Chalcolithic steatite plaque showing a cattle-drawn sledge*

18 Modern-day logging with draught cattle, URL: https://youtu.be/jDrAkIMF20I [23-06-22].
19 Gaastra et al. 2018.
20 Knipper 2011.
21 Anati 1975; Arcà 2003.
22 Geyh/Rasmussen 1998.
23 Littauer/Crouwel 1979; Piggott 1983.
24 Anderson et al. 2004.

Wheeled vehicles

One of the oldest examples among the variety of evidence for early vehicles[25] are the wheel and the axle from Stare Gmajne in Slovenia (***Figure 5***) ^{14}C-dated to 3350-3100 BCE[26]. The squarish axle hole of the tripartite disc wheel shows that the wheel was firmly attached to the rotating axle forming a wheelset[27] – a common trait in prehistoric vehicles around the Alps. Rock depictions from Val de Fontanalbe near Mont Bego, France, suggest that carts in this period and region were basically travois-like triangular devices with axles and wheels attached. A fragmentary object carved from a tree crotch found in Reute (Baden-Württemberg, Germany) and dendro-dated between 3709 und 3707 BCE[28] could be the front end of such a travois or triangular cart, whereas a complete specimen found at Chalain 19 in the French Jura (***Figure 6***) dated to 3015-2976 BCE bears use-wear traces at the ends of the two poles that suggest it was a travois[29]. Engravings from the megalithic tomb at Züschen (Hesse, Germany), in contrast, show two-wheeled vehicles with separate draught poles and cart bodies[30].

Figure 5 *– Wheelset from Stare Gmajne, Slowenia, late fourth millennium BCE*

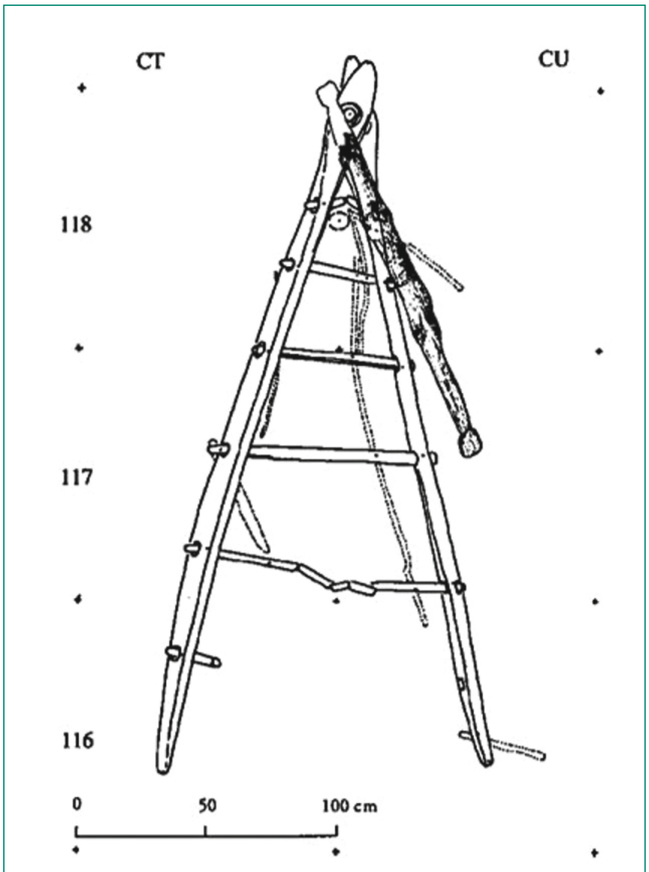

Figure 6 *– Travois and yoke found at Chalain, France*

Pictographs dated from ca. 3500-3350 BCE from Uruk (Iraq) show two round impressions under sledge symbols. If not counting marks[31], they could be interpreted as the earliest evidence for wheeled vehicles in Southwest Asia. Here, as well as in the Northern Pontic and in Northern Europe, wagons prevailed. With their four wheels turning independently on fixed axles by means of wheel hubs (***Figure 7***), they form a contrast to the wheelset carts of the alpine region. Early pictorial evidence from Europe, such as wagon-shaped ceramic cups of the Baden culture (ca. 3500-2800 BCE) or depictions on a Funnel Beaker culture vessel from Bronocice (second half of the fourth millennium BCE) complements actual wheels with hubs and axles with rounded ends including corresponding wear marks found in e.g. Gnarrenburg, mid-third millennium BCE, or the Meershusen bog, around 3000 BCE[32]. In the graves of the Yamnaya culture of the Northern Pontic steppes[33], there are also always four disc-wheels with hubs. But as with two-wheeled carts, cattle draught was paired, as copper figurines (***Figure 8***) and paired cattle burials from related cultures such as Funnel Beaker, Baden (e.g. from Alsónémedi) and Globular Amphora illustrate.

The spatial patterning of two- and four-wheeled vehicles can be explained as adaptations to hilly and flat terrain, respectively[34]. In the absence of separate brake mechanisms, the cattle team has to brake the vehicle downhill by means of the draught pole, which is much easier in a short and rigid cart construction. The different wheel principles are, in turn, likely connected to the number of axles. Wheels that rotate independently of each other enable easier cornering, as the outer wheel with the longer travel can turn faster than the inner wheel. This is true for single-axle carts, but it is more relevant for two-axle wagons. Their mass causes greater load on the individual wheel, and their wide axles cause greater difference in the travel of the wheels in the curve[35].

Cattle harness

The yoke found with the Chalain travois was only a roughly worked roundish piece of wood, so it is difficult to decide whether it was a horn or withers yoke[36], but at least one of the Val de Fontanalbe and all later depictions suggests the horn yoke as the regular yoke type in prehistory. In travoises as well as carts, a considerable

25 Burmeister 2017.
26 Veluščček et al. 2009.
27 Bulliet 2016:80.
28 Mainberger 1997.
29 Pétrequin et al. 2002.
30 Kappel 1981; Hansen et al. 2021.
31 Burmeister 2004a.
32 Milisauskas/Kruk 1991; Burmeister 2017; Maran 2017.
33 Reinhold et al. 2017.
34 Sherratt 1986.
35 Bulliet 2016; Masson/Rosenstock 2011.
36 Pétrequin et al. 2002.

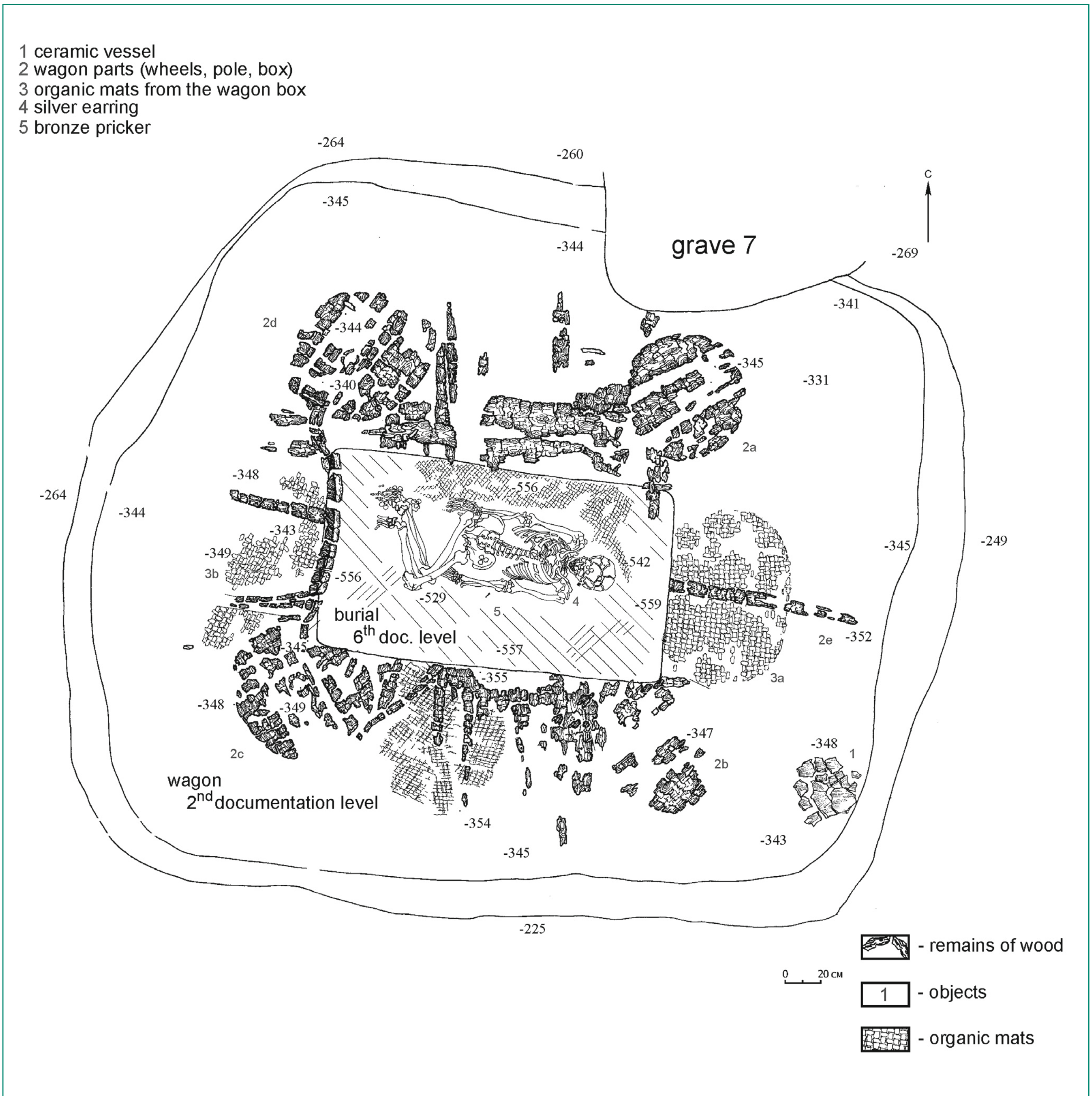

Figure 7 – *Yamnaya burial including a wagon with four wheels from Sharakhalsun 6 Kurgan 2, Russia*

Figure 8 – *Copper model of a cattle team from Bytyń, Poznań/Poland – probably late fourth millennium Funnel Beaker culture*

part of the load rests on the animals. A combination of horn yoke and cart is not uncommon[37], but puts extra strain on the animals in comparison to a cart with withers yoke or a four-wheeled wagon with horn yoke. While the fastening of front and neck yokes may result in chafing on the horn, the horn sheaves usually do not survive in the archaeological record. Hence, damaged horn cores such as in the find from Holubice (***Figure 9***) represent exceptional cases: either chafing was so severe that the bone underneath the horn was also affected or – more likely – the animal had lost the horn sheave by accident[38]. But in general, this find fits into a trend of increasing osteological evidence for physical strain on cattle from the

Figure 9 *– Worn horn core from Holubice, Bell beaker period, early third millennium BCE*

late fourth millennium BCE onwards[39]. Other yoke finds, such as from Arbon-Bleiche 3 (3384-3370 BCE), Vinelz (28th century BCE) and Chalain 2 (27th to 26th century BCE) have anatomically shaped recesses typical for withers yokes. With its comparatively small width of only ca. 1 m compared to 1.3 m to 1.7 m as in other finds, the yoke from Arbon-Bleiche[40] is too small to leave space for a draught pole between grown up animals, so it was either used for smaller animals such as goats or for training young cattle without a vehicle. The first known cases of genetic hornlessness, recognisable in cattle skulls by a characteristic cusp in the neck, appear in the fourth millennium BCE, too[41]. Given the spontaneous mutation rate of the underlying genes and their associated effects on other bodily traits such as eyelashes and genitals[42], their occurrence at a time when first dung finds (e.g. from Thayngen-Weier or Pestenacker) demonstrate livestock keeping close to the dwellings or even in stables appears[43] seems no coincidence: in crowded situations, hornless cattle are less likely to hurt each other, but they can – of course – not be harnessed with a horn yoke. As suggested by Yamnaya copper finds, cattle were steered using nose rings[44].

Hollow ways and wooden tracks

Often-used tracks would cause wheels to slide in the mud, especially in rainy weather. To prevent sliding and consequently uneven wearing of the wheels, felloes were frequently studded with metal nails in the third millennium BCE of South-west Asia[45]. In Europe, wooden tracks preserved in bogs likely served the same purpose. With widths between ca. 2,40 m and 4 m, they were broad enough for early wagons with their gauges between 1,2 m and 1,6 m, and the lack of curves suggests that early wagons had indeed no steerable front axle as suggested by traces of wear on preserved wagon parts[46]. Hence, draught poles were likely rather long to give more leverage facilitating the job of the cattle team if a wagon must go around a curve.

Later Bronze Age ca. 2000-1000 BCE

Equid domestication

Remains of domesticated African wild ass (*Equus asinus*) have been found in archaeological contexts in North-east Africa from the fifth millennium BCE onwards; from the fourth millennium BCE onwards, they also appear in South-west Asia. Attempts at domesticating the Asiatic wild ass or Onager (*E. hemionus*) led to the first hybrid animals created by humans shortly before the domestication of the horse[47]. Several horse populations of Eurasia also including the Przewalsky's horse (*E. przewalsky*)[48] were intensively exploited from the fourth millennium BCE onwards[49]. Here, one population from the Volga-Don region has been determined as ancestral to the modern domestic horse (*E. caballus*) using genetic evidence. Selected traits in these early domestic horses included genes connected to greater docility and stress-resilience as well as better performance in running and weight bearing[50]. Such traits were highly desired if we look at the Kikkuli-text, a 2nd millennium BCE training instruction for chariot horses found in the Hittite capital in Central Anatolia[51]. It hence seems plausible that the development of a related technology for light-weight vehicles in the region accompanied the expansion of the horse into South-west Asia and Europe around 2000 BCE[52]. As, however, also in South-western Asia experiments with lighter equid draft were made since the third millennium BCE, the direction of influence is still a matter of debate[53].

37 Silvester 1980.
38 Peške 1985; Benecke 1994, 273.
39 Hüster Plogmann 2002; Johannsen 2006; Milisauskas/Kruk 1991.
40 Leuzinger 2002.
41 Benecke 1994, 273; Müller 1963.
42 Wiedemar et al. 2014.
43 Ebersbach 2002.
44 Reinhold et al. 2017.
45 Mühl 2014.
46 Burmeister 2004b, id. 2018.
47 Bennett et al. 2022; Grigson 2012; Milevski/Horwitz 2019; Mitchell 2018; Wang et al. 2020.
48 Gaunitz et al. 2018.
49 Anthony/Brown 2011; Outram et al. 2009.
50 Librado et al. 2021.
51 Raulwing 2005; Starke 1995.
52 Grigson 2012; Librado et al. 2021.
53 Burmeister/Raulwing 2012; Chechushkov/Epimakhov 2018.

Chariots and spoked wheels

Judging from pictorial evidence such as the so-called Standard of Ur (***Figure 10***), not only cattle, but also donkeys or onagers were harnessed in the early third millennium BCE in front of heavy four-wheeled wagons with a parapet. Moreover, models of so-called straddle-cars and carts with a platform for standing drivers were attempts at developing lighter two-wheeled vehicles pulled by up to four equids. While wheel construction in South-west Asia and Europe only experienced minor progress in later prehistory, mainly by reducing material needed by lunate openings[54], the oldest evidence for spoked wheels, a key trait of true light-weight vehicles, is associated with the horse in what today is Southern Russia. Here, carts buried at Sintashta (***Figure 11***) and related sites dating to the beginning of the second millennium BCE[55] had two wheels of approx. 1 m diameter. Judging from traces they left in the ground, the felloes and spokes were max. 4 to 4,5 cm thick[56], pointing to advanced woodworking techniques such as bending and the lathe. The association of the wheels with horses is clear from the deposition of horse skeletal remains as well as bridle cheek-pieces, but whether the vehicle bodies were made from massive wood or a frame with trellis or whether the body's opening was towards the rear or the front remains unknown. In somewhat later vehicles with similar multi-spoked wheels from late second millennium BCE Lchashen in Armenia, however, a light framework with interwoven leather straps has been preserved that opens to the front and suggests a seated driver. Chariots with front parapets and rear openings for standing drivers as in the older four-wheeled wagons, but with spoked wheels, however, do not predate depictions from the 18th/17th centuries BCE in South-west Asia and hence suggest a merging of pre-existing South-western Asian vehicle concepts with the horse and new wheelwright techniques as Eurasian innovations[57].

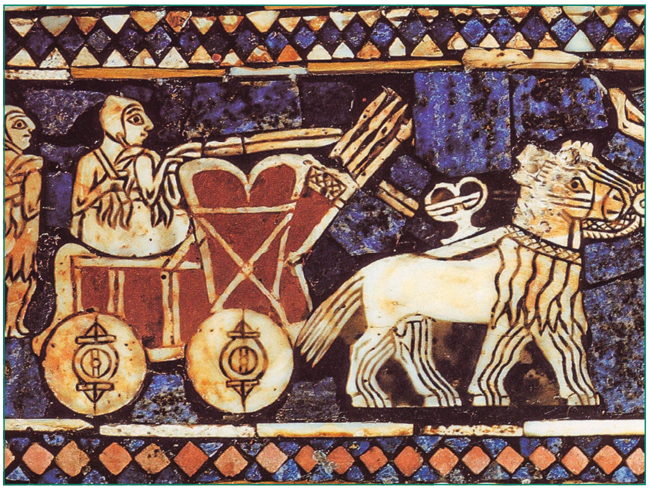

Figure 10 *– The Standard of Ur showing equids, likely onagers or hybrids between donkeys and onagers, pulling a four-wheeled wagon*

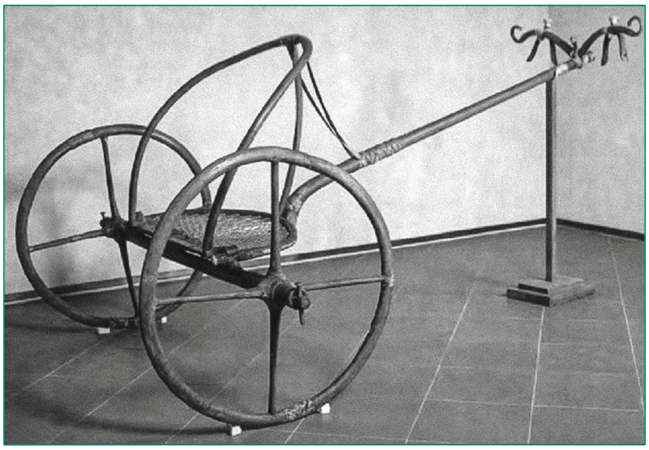

Figure 12 *– Egyptian wooden chariot, 18th Dynasty, currently in the Museum of Florence*

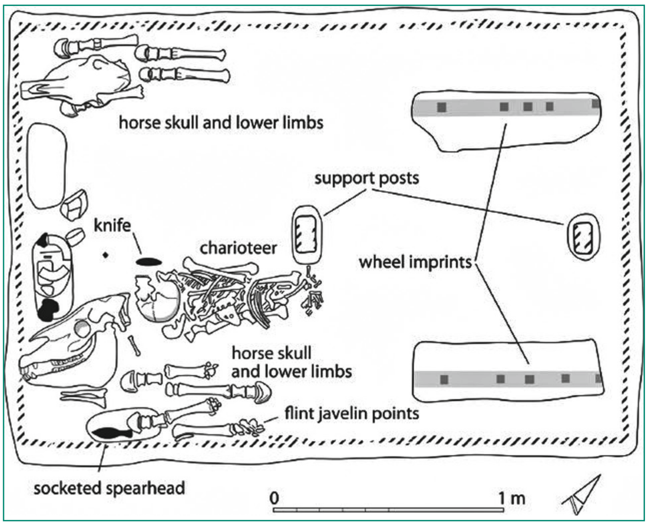

Figure 11 *– Remains of an early second millennium BCE burial of a male with remains of weapons, two horses and a two-wheeled vehicle from Sintashta Mogila Grave 30*

With only four spokes per wheel and ca. 25 kg total mass only, the developed Late Bronze chariot was extremely light and – consequently – did not require studded felloes[58]. By the second half of the second millennium BCE, such chariots (***Figure 12***) were used for cruising (***Figure 13***), hunting and warfare and formed an integral part of South-west Asian and Mediterranean and European elite lifestyle[59]; Egyptians perhaps lampooned people as only superficially integrated into Egyptian culture by showing their chariot as cattle-drawn[60], and an increasing symbolic charge of wheeled vehicles is visible in specimens like the Trundholm sun chariot (***Figure 14***). For a south-facing onlooker, the bright gilded side is visible when the vehicle is moved from East to West, while the return travel from West to East displays the dark side, mimicking the daily cycle of the sun's movement across the sky and reminding us of the ancient Greek mythological association of the sun god Helios with a chariot.

54 Piggott 1983; Lindner 2021.
55 Id. 2020.
56 Piggott 1983; Burmeister 2017; Lindner 2021.
57 Piggott 1983; Lindner 2021.
58 Mühl 2014.
59 Lindner 2021; Metzner-Nebelsick 2003; Pankau/Krause 2017.
60 Masson/Rosenstock 2011; Burmeister 2013.

Figure 13 *– Women driving a chariot. Reconstructed fresco from the palace at Tyrins/Greece, second millennium BCE*

Figure 14 – The so-called sun chariot from Trundholm/Denmark, ca. 1400 BCE

Yoke adaptations for equids

With their different physique, horses cannot be harnessed with a cattle yoke without specific adaptations. The archaeological record in the Bronze Age Eurasian steppes has not preserved remains of horse gear, but petroglyphs – that are, however, admittedly difficult to date – suggest yoke-like constructions[61] as in the early equid draft of South-west Asia[62]. Assuming that the blueprint for harnessing horses was the cattle horn yoke, depictions showing yokes close to the horses' nape of the neck do not seem entirely improbable as early stages of a technology transfer and have – moreover – proven functional in experiments[63]. Models and actual yokes such as found in Egyptian graves of the New Kingdom (***Figure 12***), however, show withers yokes additionally fastened by straps, often aided by a fork-like device to embrace the animal's lower neck. Suited mainly for light draught, this type of horse harness instigated a long-lasting division between heavy cattle draught for freight carts and wagons as well as the ard on the one and light horse draught for travel and race vehicles on the other hand.

Sequel: Iron Age and later periods

From ca. 1200 BCE onwards, the Iron Age in South-west Asia and the Eastern Mediterranean sees the transformation of the ultra-light chariot into a heavier, sturdier and more harnessed vehicle as described in Homer's Iliad that had, consequently also studded felloes[64]. In Europe, spoked-wheeled wagons appear as burial gifts. Judging from associated bridle finds, these wagons were likely horse-drawn, and in some of them a pivoted front axle is plausible[65]. Interpretations often revolve about the ceremonial use of such vehicles, but the four matching wheels from Stade (Germany) show that draught was heavy and frequent enough to require studded felloes[66]. In the later European Iron Age from ca. 400 BCE onwards, two-wheeled chariots are also known as grave goods[67]. How these Iron Age roots evolved into the known spectrum of Roman vehicles such as the four-wheeled *raeda* and the two-wheeled *cisium*, however, has not yet been the subject of targeted research[68] despite the important role roman technology had for the development of medieval animal draught technology[69]. Merowingian kings reported to travel their realms on cattle-driven wagons[70], however, are apparently a case of satire[71] similar to the Egyptian example mentioned above, as both medieval South-western Asia and Europe saw the rise of riding – on camels[72] or on equids – for personal transport and warfare until the resurge of wheeled travel with carriages from ca. 1400 CE onwards[73].

Animal traction and acceleration in prehistory

The revolute joint and the first machines

From the record outlined above, the appearance of what is colloquially called the "wheel" was key to the change in intensity in animal traction we observe around ca. 3000 BCE. However, the word "wheel" does not technically correspond to a technical or kinematic concept. Hence, the popular idea of the "invention of the wheel"[74] has prompted common misunderstandings in prehistoric research, as wheel-shaped objects such as spindle whorls and evidence for rotary motion predate wheeled vehicles by many millennia: judging from Middle Palaeolithic twisted threads[75], mankind has known how to use rotary motion since at least the time of the Neanderthals, and Neolithic fibre spinning by means of a spindle[76] is just an extension of this principle: ceramic spindle whorls are rare, but attested since the seventh millennium BCE[77]. However, despite the superficial resemblance of a spindle to a wheel attached to an axle[78], the rotary motion of a twisting spindle is not the pivoted motion that constitutes the kinematic pair of a wheel-and-axle. Rather, a spindle stick and a whorl form the spindle as a typical composite tool. Spindle and thread form what Miriam Haidle has termed a complementary toolset[79]. Here, like with bow and arrow, it is the constant control of the skilled human that keeps the active parts, i.e. the spindle and the thread, moving correctly. In contrast, in the respective machines, i.e. in the crossbow or the spinning wheel, the correct movement of the parts is ensured by joints in which the crossbow bolt or the spindle can move only in the desired direction. In that sense, the rotary motion of a roller bearing is only a complementary tool use, as the rollers must be steered by humans. Wheelsets (***Figure 15 left***), in contrast, do not require human interference due to pivoted motion in the revolute joint formed by the axle bearings. The same is true of wheels rotating around the axle (***Figure 15 right***), kinematically speaking levers that turn

61 Chechushkov/Epimakhov 2018.
62 Littauer and Crouwel 1979.
63 Spruytte 1983.
64 Mühl 2014.
65 Koch 2006; Lindner 2021; Pare 1992; Piggott 1983, 138-194.
66 Mühl 2014.
67 Piggott 1983; Crouwel 1992; Id. 2012.
68 Raepsaet 2009.
69 Holmes/Thomas (in this volume).
70 Masson/Rosenstock 2011; Murray 1998.
71 Kölzer 2004.
72 Bulliet 1990.
73 Id. 2016, 132.
74 Kaiser 2010.
75 Hardy et al. 2020.
76 Langgut et al. 2016.
77 Barber 1991; Çilingiroğlu 2009; Levy/Gilead 2013; Schoop 2014.
78 Klimscha 2017.
79 Haidle et al. 2015.

around a fulcrum[80]. After a long development of human tool use from basic to modular, composite and finally complementary use[81], the revolute joint around 3000 BCE constitutes the first attested moveable connection between components, and numerous applications of this new principle appear in the two millennia on either side of 3000 BCE[82].

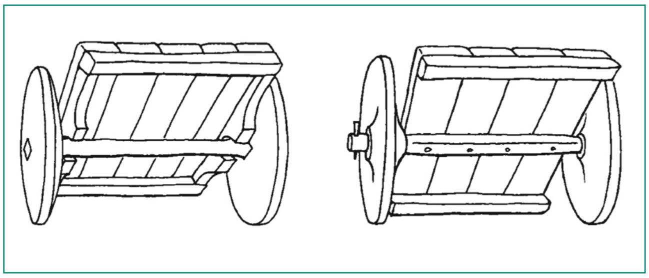

Figure 15 *– Andrew Sherratt's rotating axle principle (left) can be called a wheelset, a technical term actually derived from railroad vehicles, and is in kinematic a terms of a wheel-and-axle – rotating wheels (right), in contrast, are wheels in both technical and kinematic terms*

One of the oldest examples is the door from Robenhausen (Switzerland), the first pivoted door among other later specimens from both wood and stone[83]. With a date around 3700 BCE, the Robenhausen door supports the idea that animal figurines from the Northern Pontic Tripol'e culture that are somewhat unreliably dated to the first half of the fourth millennium BCE[84] might have held in their pierced legs revolving wheelsets predating actual wheeled transport (***Figure 16***) and raises the idea that the wheel-and-axle (or rotating axle, as Sherratt has put it) principle might somewhat predate the lever or fixed axle principle of wheeled vehicles[85]. Even though the two principles seemingly appear contemporaneously in the archaeological record[86], the kinematically entirely different mechanisms underlying the wheel-and-axle on the one and the lever on the other suggest that what is perceived as "the wheel" are in fact two separate innovations. Further applications of the wheel-and-axle are the potter's wheel and the lathe[87] – the latter in itself a prerequisite for

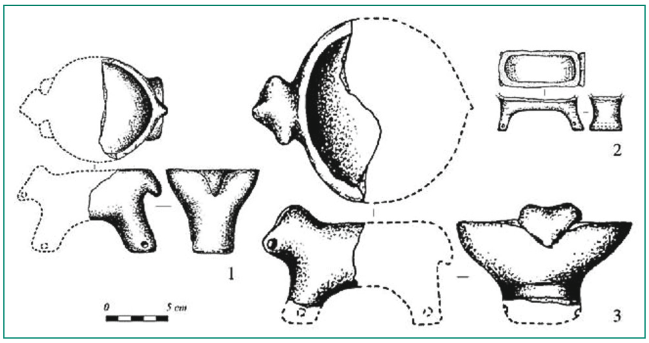

Figure 16 *– Chalcolithic animal figurines with pierced legs from sites of the Tripol'e B2 and C1 cultures, early fourth millennium BCE*

80 Reuleaux 1875.
81 Haidle et al. 2015.
82 Rosenstock 2020.
83 Altorfer 1999; Gauron/Massaud 1987; Klimscha 2017.
84 Burmeister 2004; Matuschik 2006, 281.
85 Bulliet 2016, 72. Chub, in prep.
86 Burmeister 2017; Maran 2017.
87 Cartwright 2005.

the construction of advanced vehicles , while the lever principle is used in well sweeps[88] and balance scales[89], innovations that are all first attested in the third millennium BCE. They all can be called the first machines in human history.

While a somewhat unprecise use of the term "machine" can be observed in ethnographic and prehistoric research[90], moveable connections are the defining criterion of the ISO 12100:2010 norm for the term machine as an "assembly, fitted with or intended to be fitted with a drive system consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application". This machine definition is in line with 19th century CE approaches, such as by the engineer Franz Reuleaux[91] who still knew about the use of human, animal, wind and waterpower rather than only steam, combustion and electricity. However, it is not in line with the Machinery Directive of the European Union, which excludes directly applied human and animal power. But 2006/42/EU is inconsistent, as it tolerates human and animal power for some machines such as the block-and-tackle, and hence we can safely posit that the revolute joint constituted the first machines in the fourth millennium BCE. Likely initially merely manual machines – such as pivoted doors and perhaps wheeled toys of the fourth millennium BCE – soon were combined with pre-existing Neolithic knowledge of cattle traction to become automotoric.

Work speed and travel speed in early animal draft

Why carts and wagons were developed in the first place is an interesting question that has not yet been convincingly answered and may lie anywhere between ritual and utilitarian purposes[92]. Here, the hypothesis that Neolithic economy was in broad terms labour-limited, whereas only in later prehistory economy became land-limited[93] can be helpful to understand the – despite all symbolic meanings of wheeled vehicles – practical initial reasons for inventing carts and wagons and the apparent lack of ards before the end of the Neolithic. Although according to our definitions the ard is not an automotoric machine like carts and wagons, but an automotoric composite tool, its development appears connected to wheeled transport as another means of reducing the necessary input of manpower into production. The ard significantly increases the area that can be cultivated in comparison to hoe-based culture[94] and consequently the amount of harvest to be transported. The same applies to other bulk materials that are new in the Final Neolithic and Chalcolithic such as ore from extractive metallurgy[95] as well as soil, rubble and other material for monumental mounds[96]. Sledging and logging have high friction coefficients and, hence, Neolithic animal traction was likely rather slow. Roller bearings, albeit not attested in the archaeological record[97], can potentially reduce friction, as we demon-

88 Rost 2017.
89 Genz 2015.
90 Bleicher 2018; Gleser 2016; Leroi-Gourhan 1943; Id. 1945; Id. 1965.
91 Reuleaux 1875, 38.
92 Maran 2017.
93 Bogaard et al. 2019.
94 Kerig 2013a; Id. 2013b.
95 Bulliet 2016.
96 Müller 1990a; Id. 1990b; Rosenstock et al. 2019b.
97 Harris 2018.

strated during our trials at Domäne Dahlem in Berlin in 2016[98]. However, frequent breaks between hauling intervals are necessary in which a team of several people shifts the rollers and realigns the bearings, so roller bearings, if used at all in the Neolithic, caused an intermittent and consequently equally slow workflow. With a cart or wagon, in contrast, only one person is necessary to control the animals. Moreover, they can seamlessly pull for hours and for as long as the oxen can work – i.e. about half a day[99] – and, hence, helped to transform early economies from slow and labour- to fast and land-limited. Although soon to be complemented by the horse for fast draught, cattle traction continued into the modern era, as many contributions in this volume show.

Whether horses were even herded and let alone ridden in Eurasia before they were harnessed to two-wheeled vehicles in the early second millennium BCE remains an open question, as archaeochemical evidence for equid milk consumption and signs of bridling wear on equid teeth detected in fourth millennium BCE sites[100] have recently been challenged[101]. Goat and sheep have a strong herd instinct that makes them easy to shepherd, and cattle – like donkeys - tend to face potential threats. Horses, however, have a pronounced flight instinct that makes it virtually impossible to herd them as a pedestrian, and this may have been one of the reasons behind the desire of early Eurasian pastoralists to speed up – besides, of course, the joy the new velocity brought about. Whether early draft horses were mainly trotters or ran in full gallop as shown in later second millennium BCE chariot depictions from Egypt (***Figure 17***), or whether at least some of them had genes determining pacing that are currently first attested in the Medieval era[102] remains to be investigated; more knowledge about early horse gait may help to better understand the Kikkuli text[103] as well as rhythm perception of charioteers and – from at least the first millennium BCE onwards[104] – horse riders in the ancient world. Equids, hence, can be seen as a first attempt at finding other and faster motors than cattle. However, horses increased only the travel speed of prehistoric societies. And although this faster travel speed implies a wide range of potential and yet underexplored effects on realms like communication, migration, and warfare, work speed and therefore the pace of production remained determined by cattle until the horse collar enabled the use of the horse also in heavy traction in the Medieval[105].

Over time, not only every suitable large domesticate including camels[106] and reindeer[107] has been harnessed for traction. While sailing ships represent later prehistoric instances of the use of inanimate powers such as the wind, and water power has been known since at least the Roman era, vehicles have been driven by animals until the steam engine, an innovation that has been argued to be one of the drivers of the acceleration of life observed by a number of philosophers and historians. Both, the invention of the revolute joint around ca. 3000 BCE and the harnessing of new motors around 2000 BCE, significantly accelerated work and travel speed of prehistoric societies. In a similar way, the industrial revolution around ca. 1800 AD and the subsequent rise of new motors such as the steam engine, combustion and electricity accelerated human life even further. Modern experiences of acceleration have been the subject of research by e.g. Paul Virilio, Reinhart Koselleck and Hartmut Rosa[108], and it can be fruitful to view prehistoric technical developments such as animal draft also from the angle of awareness of time in space and, hence, speed.

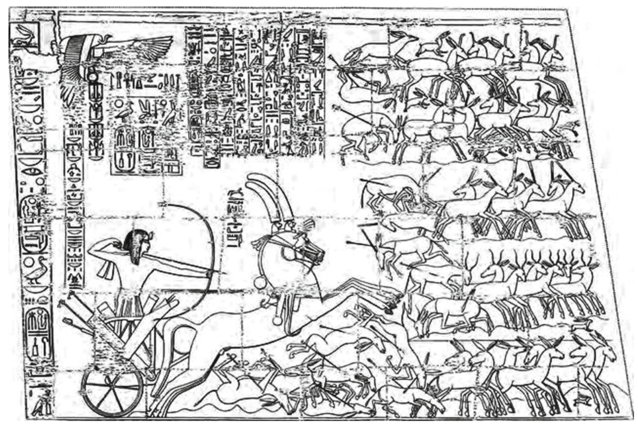

Figure 17 *– Pharaoh Ramesses III. hunting with bow and arrows and a chariot (Medinet Habu, 20th dynasty)*

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98 Rosenstock et al. 2019b.
99 Masson 2015.
100 Anthony/Brown 2011; Outram et al. 2009.
101 Taylor/Barrón-Ortiz 2021; Wilkin et al. 2021.
102 Wutke et al. 2016.
103 Raulwing 2005; Starke 1995.
104 Littauer/Crouwel 1979.
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107 Losey et al. 2021.
108 Virilio 1989; Koselleck 2000; Rosa 2005.

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