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Questioning Diversity (of Iron) in the Workplace: Bloomery Iron, Cast Iron, China and the West

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The Iron Ages in the West and China did not start with the first appearance of iron but with the first functional applications of iron. Although the initial trajectory leading to these applications was similar in both regions, the West entered its Iron Age with bloomery iron, while China replaced bloomery iron with cast iron. Our zoomed-out approach suggests that this divergence had very little to do with differences in technological capital between the two regions, but was influenced mainly by the applications demanded of iron within the respective socio-political environments. We propose that access to the technologies associated with bronze and pottery, to mass produce cast iron, differentiated China from the West and set each region on its respective course. We further propose that the West's trajectory to adopt bloomery iron was fixed through its reliance on specialists (blacksmiths) who could work independently of these technologies. China's trajectory to adopt cast iron was fixed by the socio-economic powerbase required to set up a cast iron industry at a state level, which was reinforced by an Imperial monopoly from the Han dynasty. Essentially, we have investigated why the West did not develop cast iron technology earlier than China, and why China developed cast iron technology 2000 years before the West.

1. Questions for Early Western and Chinese Iron

Pliny the elder (23–79 CE) appears to have been aware of Chinese iron (Pliny NH XXXIV. XLI. 143-146 trans. H. Rackham 1938, 233):

> But of all varieties of iron the palm goes to the Seric, sent us by the Seres with their fabrics and skins. The second prize goes to Parthian iron;…

Regardless of whether there was direct contact between Europe and China — for example the Roman historian Florus (1929 ; *The Epitome of Roman History, Book II, XXXIIII*) wrote of envoys between the 'Seres', the Silk people (i.e. the Chinese), and the Emperor Augustus (27 BCE–14 CE), or whether exchange occurred along the silk routes — the presence of Chinese iron in Europe at the time of Pliny suggests that iron of the Han dynasty (Western Han: 206 BCE–9 CE; Eastern Han: 25–220 CE) had reached the Roman Empire.

An important question then emerges: *Did knowledge and know-how of the Chinese method of making the high-quality iron that Pliny mentions also travel west?* The repercussions of transmission are significant, because iron used in Europe at the time of Pliny was bloomery iron, made using the *direct process*, while Chinese iron was cast iron, made using the *indirect process*. Another question also emerges, regarding the inception of cast iron: *From where was the cast iron technology in China (and, more importantly, its cast iron industry) derived?*

However, questions surrounding bloomery iron, cast iron, China and the West are often conflated, resulting in confusion over what is being investigated. For instance, another question that is often asked is: *Why did the West not develop cast iron technology earlier than China?* And a related, but different, question is: *Why did China develop cast iron technology 2000 years before the West?*

In this article, we examine the technological and social aspects of bloomery and cast iron, not only in terms of the products for which they were used, but also the processes used to make them, which allows the questions posed above, and others like them, to be investigated. We simplified our study by limiting it to two regions, China and the West, to examine what led to their respective approaches to iron. Reducing the vast geographical areas of both China and the West in this way may appear to be an oversimplification: China was far from unified at the beginning of its Iron Age, and the West clearly encompasses disparate regions, from the Near East to western Europe. However, we use these terms as shorthand for regions where distinct iron technologies were adopted. In essence, we are comparing the two ends of the Eurasian Steppe. This is not done for brevity but, because the topic is complex, to provide a zoomed-out view that we feel is needed to contextualise the issues before the significance of more nuanced interpretations can be discussed. We are advocating a top-down approach in order to make general statements that can inform on iron production within, near and between these regions.

We start our approach by presenting a table of chronologies for iron in the West and in China, in order to orientate readers (Table 1), who will soon notice that many of these dates are disputed, subject to caveats, or both. We also use the term *functional* iron, rather than Snodgrass's (1971; 1980; 1982) 'working iron', because we want to differentiate between prestige iron objects that were probably not considered functional (although even a prestige knife could be used as a practical weapon if necessary), iron objects that appear to have practical applications but catered for an elite market (high-status functional), and objects made of utilitarian iron, such as iron used for domestic or agricultural implements and common weapons. We are not proposing a new model for the Early Iron Age (EIA) in the West, but align with Sherratt (1993; 2000; 2016) for continuing commercial activity in a more decentralised form after the so-called Bronze Age collapse (*c*. 1200 BCE); that is, iron was an ideal product for the growing sub-elite market. However, we also recognise, for example, that the Aegean did not pass into the full 'age of iron' until the ninth century BCE (Snodgrass 1980, 354–355; Dickinson 2006, 149), Egypt did not use large numbers of iron tools until the seventh century BCE (Ogden 2000), and the Iron Age in Britain only began in earnest between 500 and 400 BCE (Tylecote 1962, 175).

Table 1 therefore summarises the chronologies mentioned in the text for China and the West. We have assigned dates (underlined in Table 1) for when iron appears to have been first produced for high-status functional objects in the West and utilitarian objects in China, and thereby propose that the Iron Ages started in the eleventh century BCE in the West and in the sixth–fifth centuries BCE in China.

Table 1: Chronologies of bloomery and cast iron in the Early Iron Ages in the West and China. Note that that many of these dates are disputed, subject to caveats, or both.

	First appearance		**First production**		**First prestige/ functional objects**	**Utilitarian objects**	
	Bloomery	**Cast**	**Bloomery**	**Cast**	**Bloomery**	**Bloomery**	**Cast**
The West	#14th BCE	*5th BCE*	#14th BCE	#14th CE	#14th BCE (prestige) **11th BCE** (high-status functional)	11th–10th BCE until historical times	#14th CE until modern times
China	*14th BCE*	8th BCE	*10th BCE (Xinjiang)/8th BCE (Central Plains)	6th–5th BCE	8th–6th BCE (prestige)	*7th–5th BCE*	**6th–5th BCE** until modern times

All dates refer to centuries, i.e. 8th BCE is the eighth century BCE. Where there is a hash (#), see text and references for alternative dates. The asterisk (*) denotes that the first production date was inferred from a substantial numbers of finds. Dates in italics are from isolated finds. Bold and underlined dates denote when iron was used for functional/utilitarian objects and where we place the start of the respective Iron Ages in the West and China.

2. Direct or Indirect?

On first inspection, bloomery iron and cast iron production would appear to be mutually exclusive. In fact, the terms *direct* (solid-state iron reduction to produce bloomery iron) and *indirect* (iron production in the liquid state through the introduction of carbon to produce cast iron) suggest opposing processes (see Tylecote 1992, 49; Craddock 1995, 236). However, in addition to the unagglomerated lumps of white cast iron, often referred to as *gromps* (Historic England 2015), found in bloomery slag, there is increasing evidence that bloomery furnaces can produce cast iron (Crew 2004) 'in some quantity and without particular difficulty', when a higher air rate (and, therefore, a charcoal burning rate) to usual bloomery iron smelting is applied (Charlton *et al*. 2010; Crew *et al*. 2011, 258). The mechanism for how cast iron is produced inside a bloomery furnace is still unclear (Forbes 1950, 405–412; Wrona 2013; see a description by Sauder (2013) for adding carbon to bloomery iron to initiate localised melting to make steel in an 'Aristotle furnace'). Nonetheless, the terms *direct* and *indirect* are confusing, as bloomery iron requires the addition of carbon (often at the hearth) to make it harder and stronger, and cast iron requires the removal of carbon (by annealing or fining) to make it less brittle.

Bloomery iron became the main precursor for iron objects in the West from around 1000 BCE; there is no substantial evidence of iron smelting, furnaces or slag, in the Middle East prior to this time (Erb-Satullo 2019). There are earlier sporadic iron finds in Europe, Egypt and the Near East (Pleiner 2000, 7–8). However, it is difficult to place a date on when bloomery smelting began. Some early iron finds are clearly meteoritic, having a high nickel content (Tylecote 1962, 9–13, fig. 1; Craddock 1995, 103–109; Jambon 2017). It is also possible that iron smelting began as a by-product of developed copper smelting technology (where iron ore was a flux) (Tylecote 1992, 9), because metallic iron grains can be produced in copper slag (Pleiner 2000, 12). However, iron also dissolves in copper (Tylecote 1992, 12). Moreover, although small pieces of metallic iron are found in copper smelting slags, it would be very difficult to remove the copper while leaving the iron in its metallic state (Erb-Satullo *et al*. 2014, 157). There is also no evidence of workshops indicating that both iron and copper were produced in the same location (Maddin 1982, 311; Kassianidou 1994, 76) or indications that both metals were produced in the same furnace, perhaps because of the difficulty in distinguishing copper smelting and bloomery iron slags (Pleiner 2000, 254; Rehren and Pernicka 2008, 235). There are also issues of *availability*, if iron could only be produced in regions with copper deposits, and *scalability,* because copper production would presumably scale proportionally with the amount of iron produced, which are both at odds with the term *Iron Age*. Essentially, whether iron was produced by accident (whatever that means, as we can only call something an accident if we know the original intention) or whether it was a result of experimenting with different types of ore, the process could clearly be repeated; iron that arises in the Iron Age in the West was probably the result of deliberate smelting of iron ores in archaeologically elusive bloomery furnaces.

It is probably prudent not to overemphasise the importance of historical data. However, textual evidence suggests that Anatolia was smelting iron from at least the thirteenth century BCE, for example as evidenced in a letter (KBo I 14) from King Hattusilis III (*c*. 1275–1255 BCE) of the Hittites to another, unnamed, king (translation in Collis 1984, 32):

As for the good iron which you wrote about to me, good iron is not available in my seal-house at Kizzuwatna. That it is a bad time for processing iron I have written. They will produce good iron, but as yet they will not have finished. When they have finished, I shall send it to you. Today, now I am dispatching an iron-dagger blade to you.

As alluded to above, such early smelting dates are contested. Nonetheless, the intentional (and apparently difficult) making of iron referred to in the Hittite text (KBo I 14) is perhaps a reasonable indication of when deliberate smelting of iron ores started in the West, with unforgeable iron sulphide matte found at the Hittite capital Hattusa, from a fourteenth century BCE context (Muhly *et al*. 1985), probably representing an unsuccessful attempt to smelt ferruginous arsenopyrite, pushing the date back slightly further. Moreover, written records suggest that iron was used for weapons from the New Hittite period (1400 BCE–1200 BCE) (Souckova-Siegelová 2001), which could indicate that iron ores were being smelted regularly during this period (Killick 2014, 33), although it is not clear what expertise they had in ironworking.

In China, a bizarrely early (*c*. fourteenth century BCE) bloomery iron bar from a burial site in Mogou, Gansu province (Chen *et al*. 2012), potentially made its way from the Eurasian Steppe via Xinjiang province in north-west China (even though no iron as early as this has been found in Xinjiang). Sufficient numbers of iron objects to suggest indigenous bloomery iron production appear much later, in the tenth century BCE in Xinjiang (Chen 1990; Han 2018) and the eighth century BCE in central China (Han *et al*. 1999; Chen *et al*. 2009). Nonetheless, the bloomery iron process, which probably arrived in China from the Near East in the early first millennium BCE by a similar route to the Mogou iron bar, was only used for a short time in central China (*c*. eighth–sixth centuries BCE), with bloomery iron appearing to have replaced meteoritic iron to make prestige, often bimetallic, objects, and cast iron replacing bloomery iron to make utilitarian objects. Conversely, bloomery iron was used in Europe until the blast furnace was developed around the fourteenth century CE (Tylecote 1992, 96) (although see below for alternative dates), which produced cast iron in the liquid state, about 2000 years after China.

It should be noted, however, that there are a few cases of bloomery iron being used in China after the innovation of cast iron technology (Wagner 1996; Han and Ko 2007; Chen 2014) that can be considered an alternative technological choice based on local resources and socio-economic conditions. For example, the Luojiaba site in eastern Sichuan potentially indicates a tradition of bloomery iron smelting in the southwestern minority regions of China during the Eastern Han dynasty (Sun *et al*. 2025). Moreover, bloomery smelting may still have played an important role in the ancient Loulan state, located in the Lop Nor region of Xinjiang, in the third to the fourth centuries CE (Zhang and Bahetibieke 2025). It must also be considered that some rural regions had yet to be fully consolidated into the emerging Han Empire after the fall of the Qin (221–207 BCE). Guangxi province (*c*. 400–700 CE) (Zou *et al*. 2022) and Yunnan in southern China in the tenth century CE (Zou *et al*. 2019) are areas that border southeast Asia, where traditional bloomery smelting persisted for a long time (Huang 2013; Zou *et al*. 2022). There is also very late evidence of bloomery iron smelting in Daye County in Hubei province during the Qing dynasty (1644–1911 CE) (Hu *et al*. 2013; Larreina-García 2017; Larreina-García *et al*. 2018). However, this was probably a re-introduction of bloomery technology to China, based on a Jesuit translation of Agricola's *De Re Metallica* from Latin into Chinese at the end of the Ming Dynasty (1368–1644 CE) (Wood and Liu 2025a), rather than a continuity of practice (Larreina-García 2017; Larreina-García *et al*. 2018) about two millennia after the Han dynasty imposed an imperial monopoly in 117 BCE on cast iron production (Wagner 2008, 246). Essentially, these exceptions do not significantly alter the narrative that bloomery iron vanished almost completely from China, and particularly central China, after the introduction of cast iron in the sixth–fifth centuries BCE.

There is evidence of cast iron production in the West before the fourteenth century CE. Cast iron smelting is mentioned by Agricola (1494–1555 CE) in his *De Re Metallica* (Agricola 1556, trans. Hoover and Hoover 1950, 421), but only the transition stage, progressing from the direct to the indirect method, which was a relatively new process for Europe and not explained well by Agricola, who does not mention the method of converting cast iron into wrought iron by eliminating the carbon through oxidation (Hoover and Hoover 1950, 421–423). The fining or puddling process, which was used in China from the third century BCE, did not come into use in Europe until the end of the eighteenth century CE. Archaeological evidence of cast and high-carbon iron production pre-dates Agricola's treatise, which could suggest that some early iron workers in the West may have refined and used this material. A cast iron lump was excavated from a fifth-century BCE layer at ancient Messemvria-Zone, a city on the northeast coastline of Greece (Kostoglou and Navasaitis 2006). Pleiner (2000, 247–250) and Birch (2017 , 131–144) describe cast iron finds in Europe from the Roman period. However, these rare finds do not necessarily represent intentional production of cast iron. In fact, the beginning of an intentional indirect iron-making process in the West is difficult to pin down. Val Gabbia III in the Lombard Iron district of northern Italy (Fluzin 2003; Cucini *et al*. 2020) is considered to be the earliest known site (410–600 CE) with intentional cast iron production and mastering of the decarburisation technique. Other sites across Europe also suggest production and use of cast iron and high-carbon steel in the mid-first millennium CE (see Navasaitis and Selskiene 2007). Some researchers place intentional cast iron production in the twelfth century CE, such as at Lapphyttan in Sweden (Buchwald 2003, 171), or more often between the thirteenth and fifteenth centuries CE (Van de Merwe and Avery 1982; Tylecote 1992, 96; Lucas 2005; Navasaitis and Selskiene 2007; Rawson 2023, 285).

Irrespective of the exact dates for the adoption of the indirect process in the West, any cast iron found prior to the mid-first millennium CE, and perhaps prior to the early second millennium CE, suggests that they were discarded by-products of the bloomery process that had failed to be recycled as part of the charge of the next bloomery smelt to make bloomery iron. This mechanism is supported by Crew *et al*.'s (2011) assessment of excavations at the fourteenth-century CE bloomery at Llwyn Du, North Wales, a smelting site that appears to have employed strong reducing conditions and high temperatures to produce 'steely' blooms. From the estimated 14,000 smelts carried out, only a very small number of smithing hearth cakes and lumps of discarded metal were found. Analyses carried out on two of these metallic lumps identified them as high-carbon eutectoid steel surrounded by white cast iron. This would suggest that any waste products recovered in the archaeological record at Llwyn Du had escaped recycling for the next smelt. As there are differences in efficiency when producing bloomery iron and cast iron — bloomery iron slag has about 50–75% FeO (Craddock 1995, 250; Rehren *et al*. 2007) and cast iron slag can be below 5% FeO (Zhang *et al*. 2023) — any cast iron produced from the bloomery furnace, along with iron-rich debris, would have been a welcome addition to the next charge of the bloomery if no other application for it could be found.

Early cast iron finds in the West support the narrative that cast iron can be produced in a bloomery furnace. Furthermore, at least to some degree, this answers the first question we presented: *Did knowledge and know-how of the Chinese method of making the high-quality iron that Pliny mentions also travel west?* Essentially, there is no need to consider whether knowledge and skills were transmitted from China to the West to produce cast iron. Perhaps transmission did occur, but it would not have revealed to the West anything that was not already known. Regardless of whether cast iron was only viewed as an unwanted by-product of the bloomery process in the West, the technology was there to produce it.

2.1 Bloomery to Cast Iron in China

The fact that the bloomery furnace can produce both bloomery and cast iron leads to the second question: *From where was the cast iron technology in China* (*and, more importantly, its cast iron industry) derived?*

One hypothesis is that cast iron in China emerged not out of bloomery iron production, which is considered to have been used in parallel with cast iron for at least a couple of centuries, but instead out of the furnace techniques already in use for casting bronze objects (Lam 2014), until the cast iron process was able to produce sufficiently high-quality iron products that could supplant bloomery production. However, the mechanism for such a transition is unclear because of differences in processing bronze and iron. These differences will be discussed below. While we advocate the derivation of cast iron production from the bloomery furnace (and not from bronze production per se), we recognise that we first need to clarify our position on the relationship between the bloomery furnace and the bronze industry in China.

We accept that bloomery iron objects made their way into northwest China perhaps as early as the fourteenth century BCE (Chen *et al*. 2012), dates contemporary with the earliest iron objects in the West (Pleiner 2000, 7–8), and that China acquired bloomery technology in the Central Plains about half a millennium later, when its bronze industry was flourishing. We further recognise that bronze workers were probably the first people to adopt bloomery iron technology in central China. We have no evidence of bloomery furnaces from this time and, therefore, there is no evidence of any direct connection between bloomery iron production and bronze production. However, bronze–iron bimetallic objects support a close relationship between the two metals in a way that is much less evident in the West. Essentially, bronze was *cast* on to iron blades in China to form handles (Figure 1), rather than riveted on, as evidenced by iron knives and *ge* blades at Guo cemetery, Sanmenxia (Henan) (Chen *et al*. 2018), and Liangdaicun (Shaanxi) in *c*. eighth century BCE contexts (Han *et al*. 1999). Bronze–iron bimetallic objects in China suggest that iron workers and bronze casters worked together. [A list of iron weapons and tools with rivets, attributed to the twelfth and eleventh centuries BCE from Cyprus, Syria, the southern Levant, the Aegean, Anatolia and Egypt, can be found in Sherratt (1993, appendix 1).] Such a collaboration could indicate that bloomery iron seeded a technology within the bronze industry during the Spring and Autumn period (*c*. 770–476 BCE) that stimulated the bronze industry to diversify from its traditional remit of providing ritual and prestige bronze objects, as well as bronze weapons, to the elites of the Zhou dynasty.

Figure 1: Photographs of a bimetallic knife (upper) and *ge* blade (bottom) from Guo state cemetery, Sanmenxia (Henan). Adapted from Chen *et al*. (2018).

Furthermore, the bronze industry in China had the skills to make moulds to cast their metal, such as the complex mould technology used at least as early as the Shang dynasty, which required a division of labour to make inscribed ritual bronzes (Bagley 1987; Campbell 2014). Moulds of clay, sand and silt were fired in kilns. For example, moulds and cores from the Western Zhou site of Zhouyuan, Shaanxi (eleventh–eighth century BCE), and the Late Shang site of Xiaomintun, Henan (thirteenth–eleventh century BCE), were found to have been fired at 550–650 °C (Liu *et al*. 2007, 2008) or 600–700 °C (Jin *et al*. 2015). Eastern Zhou-period moulds from Xinzheng, Henan (eighth–third century BCE), were determined to have been fired below 800 °C (Liu *et al*. 2013). Clearly, moulding technology would have benefited the casting of iron. These temperatures are also coincident with those required for decarburising cast iron through annealing (see Cast iron processing).

It has been also proposed that cast iron could have been accidentally discovered through carburising and melting iron blooms in a cupola furnace (Figure 2), a furnace that superficially resembles a small blast furnace, of the sort used for melting bronze from at least the Spring and Autumn period (Wagner 2008, 60, 119). This association would not only support a close relationship between bronze and iron production, but also that cast iron emerged because of the introduction of the bloomery furnace to China. Here, we note simply that cast iron appears in the eighth century BCE in Shanxi in central China (Han 2000) around the same time as bloomery iron, and that cast iron objects have been found in the same contexts as bloomery iron in Jiangsu in the sixth century BCE (Nanjing Museum 1974), perhaps a point of inflection reflecting a transition from bloomery to cast iron production. In fact, since the Chinese Bronze Age started in the early second millennium BCE, it is difficult to find an explanation as to why cast iron was not exploited much earlier if it had been reliant solely on the skills and techniques required to make bronze objects; that is, without the stimulus of the bloomery furnace, it is likely that there would have been no cast iron industry in ancient China.

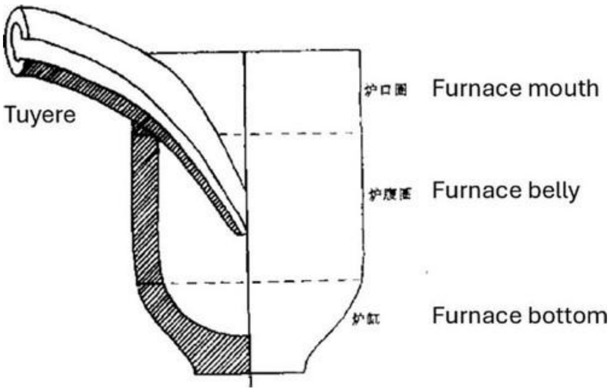


Figure 2: A cupola furnace: a reconstruction of a bronze melting furnace found in Houma, Shanxi (adapted from Li 1994, 147, fig. 74), a type commonly found at foundry sites of the Spring and Autumn period.

In essence, our stance is that cast iron in China derived from the bloomery furnace, which had first been used to make bloomery iron in the Central Plains between the eighth and sixth centuries BCE, and it was bronze workers (and those making ceramic moulds) who developed the bloomery furnace into a cast iron industry.

2.2 Bloomery to Blast Furnace in China

There are two fundamental types of bloomery furnace: bowl furnaces (basically a hole in the ground, with air supplied to the ore charge via pipes or tuyeres) and shaft furnaces (which use a natural draft and/or tuyeres) (Tylecote 1973). Both produce a solid lump of metal, the 'bloom' of bloomery iron, and neither leave much of an archaeological footprint because the furnaces are destroyed to remove the iron. Even when archaeological remains are found, they can be ambiguous. For example, the remnants of fining furnaces that were used for decarburising cast iron were initially misidentified as bloomery furnaces (Henan Provincial Bureau of Cultural Heritage 1962, cited in Needham 1964; reinvestigated by Zhao *et al*. 1985) at the early Han ironworks at Tieshenggou in Henan province (second century BCE–early first century CE). Similarly, bowl furnaces recovered at Tonglushan in Daye (Hubei province), dated to the Northern Song dynasty (960–1127 CE), were thought to have been used in bloomery smelting (Larreina-García *et al*. 2018), despite being dated to 1000 years after the Han imposed their Imperial monopoly on cast iron production; again, these bowl furnaces were probably used for fining cast iron (Wood and Liu 2025a). In effect, it is difficult to determine how furnaces evolved in China between the eighth and sixth centuries BCE to favour cast iron over bloomery iron production before the blast furnace was developed (*c*. sixth–fifth centuries BCE), because bloomery furnace sites have not been found in pre-Han dynasty China and, even if they had, it would not always be possible to determine whether the bowl was in fact the bottom of a shaft furnace.

Nonetheless, the bloomery furnace and the blast furnace are perhaps not quite as different as often depicted (see Tylecote 1992, 95–108). The fundamental reduction reactions that take place during smelting, whether in a bloomery or blast furnace, follow the sequence shown in Figure 3.

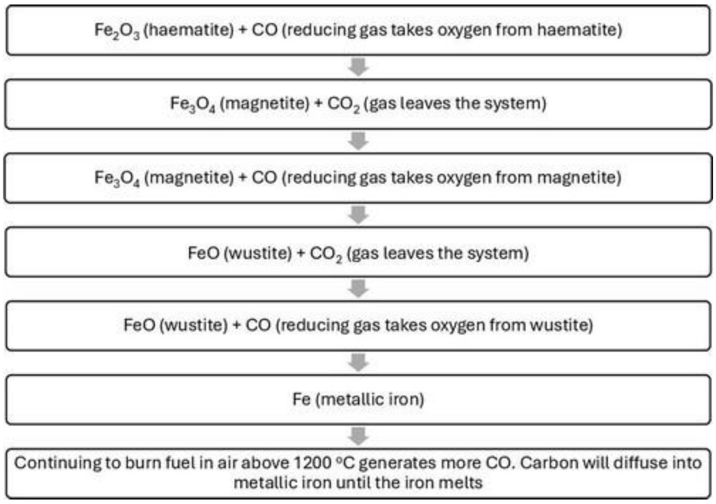


Figure 3: A schematic of the reduction reactions that take place during smelting, whether in a bloomery or blast furnace.

Whether there was an increase in the height of the shaft, and/or whether the blast furnace was influenced by the cupola furnace used in bronze making, where the air blast is carried by ceramic pipes over the top of the furnace to heat it before it enters at the bottom (Wagner 2001, fig. 6) (Figure 4a), the main differences that result in the production of cast iron are an increase in the ratio of charcoal to ore in the charge, the concomitant rise in processing temperatures, and a taphole for the removal of liquid iron. Bloomery iron production is favoured by the introduction of a smaller proportion of charcoal with the next charge, whereas cast iron production is favoured by an increase in the proportion of charcoal and tapping the iron from the furnace in the molten state (Tylecote 1962, 301).

We propose that, in China, furnaces to smelt cast iron developed from the only way to make cast iron that was available in China: from the bloomery furnace.
Furnaces *evolved* into those that permitted higher temperatures and higher air rates (and, therefore, higher charcoal burning rates) to maximise the production of cast iron at the expense of bloomery iron. If cast iron in China did not derive from the bloomery furnace, where else could it have come from?

We have answered part of the question presented at the beginning of this section, *From where was the cast iron technology in China* (*and, more importantly, its cast iron industry) derived?*, by proposing that the inception of cast iron metallurgy in both the West and China derived from the bloomery furnace; that is, both regions had access to the same technology, regardless of whether they utilised cast iron or not, but in different periods. We will now investigate how this technology became an industry in China but not in the West during their respective Early Iron Ages (EIA).

3. To Carburise or Decarburise?

China acquired bloomery technology in the Central Plains during the eighth century BCE, several hundred years after the West, and developed its cast iron industry in the sixth–fifth centuries BCE. As we will discuss later, the social and political contexts from which iron emerged in China and the West were very different, and we propose that they had a significant bearing on the trajectory of iron adoption. However, without annealing or fining to decarburise cast iron, the cast iron produced in the bloomery furnace (or any subsequent adaptation) would have been hard, brittle and, essentially, unworkable. Therefore, a more practical question needs to be asked at this stage, before addressing why China and the West adopted cast iron technology in completely different eras: *Why did China utilise this brittle material, but the West throw it back into the furnace?*

3.1 Bloomery Iron Processing

Manufacturing iron requires much more work than bronze: more charcoal and more muscle power (bellows, smelting and forging). Smelting iron is also much more variable and prone to far more mistakes than copper metallurgy (Pickles and Peltenberg 1998), partly because of the variation in ore quality and ore types; that is, the amount of gangue associated with haematite, magnetite, siderite, limonite/Goethite, and so forth. Smelting iron also requires stronger sustained reducing conditions than smelting copper: from the Ellingham diagram, reducing copper ore to copper only requires $CO/CO_2 \approx 1/10^3$, while reducing iron ore to iron requires $CO/CO_2 \approx 5/1$ (see Killick 2014, 29–34, fig. 2.3). The removal of slag is also much more important in iron production than for copper, which can be a slag-less process (Craddock 1995, 122–146; Craddock 2009, 3–11), a crucial point that makes it difficult to identify the earliest copper smelting sites (see Radivojević *et al*. 2010) and, therefore, where copper metallurgy was invented. Smelting iron ore is basically much more difficult than smelting copper ore.

Iron ore must be heated to around 1200 °C to reduce it to a bloom of relatively pure iron (Killick 2014, 11–45). As iron cannot be removed as a liquid from a bloomery furnace, the slag must be melted; that is, the gangue minerals associated with iron ore, comprising mainly silica, need to be fluxed and separated from the bloom. Nonetheless, the bloom has a lot of porosity and retains slag as inclusions, but it can be smithed because of its low carbon content; that is, by hot-working and forging. This low-carbon iron is a soft material that requires the introduction of carbon if the aim is to increase its hardness, particularly to produce an object with a durable cutting edge. This could be done during smelting, as seems to have been the case with the 'steely' blooms mentioned earlier at the fourteenth century CE bloomery at Llwyn Du, North Wales (Crew *et al*. 2011), by increasing the amount of carbon through the application of high temperatures and strong reducing conditions. However, this process would not only be very difficult to control, but also 'steely' blooms are very difficult to hammer to remove slag and work into shapes.

A more probable scenario than controlling the carburisation process during smelting, especially for nascent iron production, would be hammering bloomery iron at a charcoal-heated hearth. The process of making bloomery iron hard can be summarised as follows. The bloom is removed from the furnace as a solid mass, and hammered by smelters while it is still hot, to remove slag and to form an iron billet. These billets are forged into objects, or bars to be traded, at a hearth by blacksmiths. The repetitive process of heating, hammering and quenching the iron removes more slag (as well as breaking up ferrite, thereby providing smaller grains with various orientations) and carburises the surface of the iron (Notis 2014, 47–66). This produces iron with a hard surface that can be sharpened, and a quasi-isotropic malleable core. To produce larger or stronger objects, slabs of iron need to be forged together (i.e. the piling process), each with a 'skin' of steel (Collis 1984, 30), to form a layered composite that can be further forged and shaped.

The process of acquiring and perfecting these skills would have created specialists, iron smelters and blacksmiths, who would have been quickly identified apart from other metal workers. This statement may at first appear unqualified. However, as mentioned above, the skills for making iron objects using bloomery iron are very different to those for bronze. Hammering iron at high temperatures not only carburises the surface of iron to make it hard (work-hardening is a less important process for hardening iron than it is for bronze), and is required to forge slabs together to make larger and stronger iron objects (a process that would have been redundant for bronze), but it also removes slag from iron, which, for metals with lower melting points, such as copper, would have been removed during smelting. These processes are necessary, particularly if the aim is to compete with bronze: the Brinell hardness of cast bronze (88) is low; hammered bronze (228) is higher than that of bloomery iron (100), but lower than that of forged iron (246+) (Collis 1984, 30).

In addition to the skills required to increase the concentrations of carbon in the iron and remove slag inclusions, the blacksmith needed to shape objects with the correct balance of hardness, strength, ductility and elasticity *at the same time*: chisels and the edges of blades need to be hard but not brittle; files need to be harder than the materials they are abrading; the core of a blade needs to be flexible; armour needs to be hard enough not to be penetrated, but tough enough that any impact is absorbed by the armour and not transmitted to the person wearing it; a sword requires elasticity to spring back into shape after impact, but also needs to be hard enough to be sharpened and maintain a good cutting edge after use. This made the blacksmith a specialist who possessed skills far above those working with bronze, skills that were probably passed down over generations, and honed during apprenticeships over many years, to customise iron for a wide variety of applications and changing markets. This does not mean that blacksmiths and smelters were necessarily the same people, nor that they worked solely with iron. Nonetheless, the repercussions of requiring specialist skills to master bloomery iron, particularly to produce iron blades that were technically superior to contemporary bronzes, perhaps explains why iron was at first used for prestige rather than functional objects in the West and in China; that is, the multi-tasking skills required of the blacksmith had to be learned.

Unfortunately, evidence of smithing bloomery iron is rare in the West in its EIA and non-existent in China. A blacksmith's workshop excavated in Phokaia (on the East Aegean coast in central western Anatolia) is one of earliest known smithies, perhaps from the eleventh century BCE (Yalçın and Özyiğit 2013; Mokrišová and Verčík 2022). The carbon content of slag recovered, presumably smithing slag, varies between 0.1 and 0.8 per cent, thereby suggesting carburisation. Interestingly, unlike in the Late Bronze Age (LBA), when craft production took place within the household area (e.g. on the Liman Tepe mound, about 50 km south of Phokaia; Mangaloğlu-Votruba 2015), smithing on the Anatolian Aegean coast (e.g. Klazomenai in Ionia) in the EIA appears to have been located outside the main settlement. A similar feature has been observed at Klazomenai during the Archaic period (seventh–fifth centuries BCE), where the smithy stood next to an olive press directly in front of the city gate (Cevizoğlu and Yalçin 2012, 73–97; Cevizoğlu and Ersoy 2016, 105-–131).

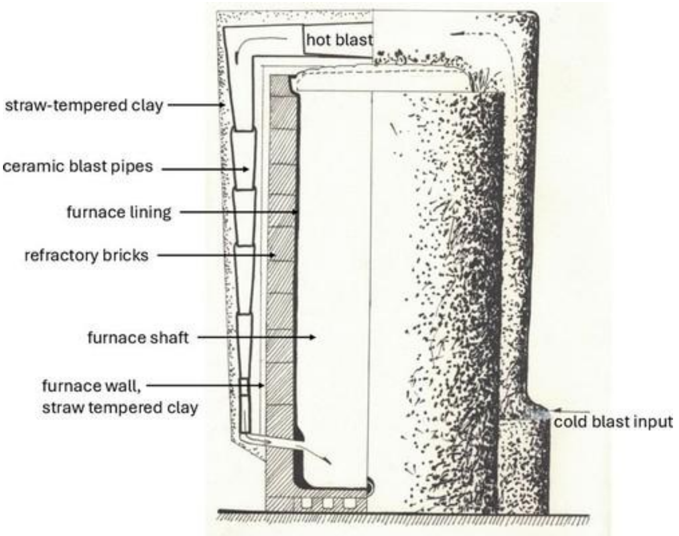
Although technological differences between processing bloomery iron and bronze and the locations of workshops in the LBA and EIA do not necessarily mean that iron was made independently of bronze in the West, these differences perhaps indicate that iron *could* have been made independently of bronze. In fact, the images of the blacksmith god of the Greeks (Hephaistos) and Romans (Vulcan) and his association with the Egyptian god Ptah, working metal independently at a hearth and living away from the other gods, perhaps fits Hesiod's Age of Iron better than Homer's Age of Bronze (Sherratt 1993; Cartwright 2019). If this were the case, and iron production in the West did not rely initially on co-crafting, it would be contrary to the situation in China where, as we shall demonstrate, the cast iron industry was inextricably linked with the technologies used to melt bronze and make ceramic moulds.

3.2 Cast Iron Processing

Melting and casting 'pure' iron requires temperatures of around 1538 °C, which were not achieved until the nineteenth century CE in Europe (Tylecote 1992, 48). Modern blast furnaces work at much higher temperatures (around 2000 °C) to achieve temperatures above the mass of ore, to melt the iron out.

Steel can be created by adding carbon to bloomery iron in the solid state (carburisation) or removing carbon from cast iron in the liquid state (decarburisation) (Craddock 1995, 237). However, as noted by Wagner (2008, 164), removing carbon from cast iron can be conducted in the solid state by annealing at high temperatures. Annealing cast iron, a process practised in China from at least the fifth century BCE, greatly facilitated the production of tools and weapons (Li 1975; Han and Chen 2013). Nonetheless, changing the carbon content is a play-off between the melting point and malleability; that is, increasing the carbon content generally decreases the melting point of the iron. A low melting point is, of course, beneficial if the aim is to cast iron in a mould. For example, bloomery iron, which generally has little to no carbon, requires temperatures approaching 1538 °C to melt it (i.e. temperatures that were prohibitively high until modern times), while iron with 2.1% carbon melts at 1380 °C, and iron with 4.3% carbon melts at 1148 °C, the latter being not far above the melting point of copper (Qian and Huang 2021). However, high-carbon iron is too brittle to undergo any subsequent shaping by hammering.

Unlike tapping cast iron from a blast furnace (i.e. removing liquid iron that flows out of the furnace before the less dense slag), cast iron would be solid when removed by the smelters from the bloomery furnace, even though it was probably formed in the liquid state inside the furnace. With its relatively low melting point as a result of its high carbon content compared with bloomery iron, it is possible to (re-)melt cast iron in a furnace, such as the Chinese cupola furnace used in bronze production mentioned earlier (Figure 2), and pour it into ceramic moulds to make objects. Furnaces used to melt iron (Figure 4a/Figure 4b) appear to have been modelled on the cupola furnace used for bronze, such as the iron melting furnace recovered at a Warring States/Han foundry located in Dengfeng, Henan, which specialised in iron agricultural tools (Li 1994) (Figure 4b).



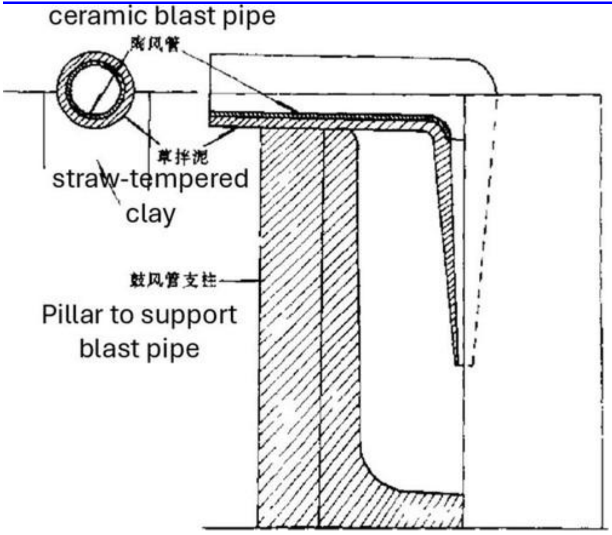


Figure 4a (upper): A reconstruction of a Han-period iron melting furnace, based on nine furnaces excavated at Wafangzhuang in Nanyang, Henan, showing that the outer diameter at the base was 2.3 m, with a height of 3–4 m (redrawn by Wang Ziyuan from Wagner 2008, 238, fig. 102). Note that the air blast is carried by ceramic pipes over the top of the furnace to heat it before it enters at the bottom.
Figure 4b (lower): A reconstruction of an iron melting furnace found at Yangcheng, a foundry located in Dengfeng, Henan, that specialised in iron agricultural tools from the Han period (adapted from Li 1994, 148, fig. 75).

The levels of slag in cast iron are low compared to bloomery iron (Zhang *et al*. 2022), and steel made by decarburising cast iron by annealing will be more durable than bloomery steel because of fewer inclusions (Bowman *et al*. 1984). Furthermore, since cast iron production has a higher iron recovery from the ore, poorer iron ores can be used to produce cast iron (Craddock 1995, 235). In fact, as anyone who has tried to smelt iron ore can attest, low-quality ores can result in failure to produce any bloom in a bloomery furnace. In effect, decarburised cast iron is perhaps preferable in terms of quality to carburised bloomery iron, although, depending on the ore, bloomery iron can be free of deleterious trace elements (Craddock 1995, 250).

If the end application does not require the object to be malleable or subsequently worked, cast iron produced in a bloomery furnace should be able to produce objects of various shapes, limited only by the mould technology available (Figure 5a). The cast iron produced would still need to be heated to around 1150 °C for it to melt, an achievable temperature for anyone familiar with casting bronze. However, there are issues with this material. Even accepting that it cannot be hammered, cooling down high-carbon cast iron from the melting temperature can cause this brittle material to crack in the mould (white cast iron often has over 50% cementite (Fe_3C)), as a result of the build-up of thermal stresses, especially with larger objects or more complex shapes (Bhiogade *et al*. 2018). There would be very few applications for this material, as evidenced in the archaeological record; for example, the earliest cast iron pieces in China, which were found in Tianma-Qucun cemetery in Shanxi province, dating to the eighth century BCE (Han 2000), and in a tomb in Liuhe county in Jiangsu province, dating to the sixth century BCE (Nanjing Museum 1974), include fragments and a deliberate spherical lump of unknown purpose. The microstructures reveal that they were white cast iron, which was too brittle to use on a large scale (Qian and Huang 2021).

Another route for cast iron is to make it malleable. Leaving aside the later processes of fining (and puddling) and focusing on annealing, cast iron lumps emerging from the bloomery furnace can be heated up and held at temperatures between 700 °C and 1000 °C in an atmosphere low in oxidising potential, such as in a closed container, resulting in the primary cementite decomposing to iron and free carbon (Rehder 2000). This process decarburises cast iron: carbon dioxide from burning charcoal reacts with free carbon in cast iron to form carbon monoxide (i.e. $CO_2 + C \rightarrow 2CO$), which diffuses out of the iron. Of course, lumps of iron would take a long time to decarburise, with larger lumps taking much longer than smaller lumps; that is, the bulk of a cast-iron lump could remain carbon-rich and, therefore, brittle. Even if a lump could be fully decarburised, its melting point would be too high to cast into a mould. However, it could be hammered and, therefore, if lumps of iron after annealing were insufficiently malleable to hammer, they could be returned to the annealing kiln (Figure 5b). Note that we use the term kiln here, rather than furnace, as annealing can be conducted at temperatures commonly used to make ceramic moulds (see Bloomery to cast iron in China) and pottery (see Access to technology to produce cast iron).

Alternatively, cast iron removed from the furnace can be cast into billets prior to annealing (Figure 5c). Decarburisation may still take a long time, but this step has the advantage that annealing parameters (times at temperature) can be determined empirically; that is, billets of uniform size and shape will decarburise at similar times. However, again, the bulk of a cast-iron billet could remain carbon-rich, with decarburisation occurring only at the surface. In effect, although the billets can be cast into ceramic moulds, the moulded objects could still be brittle. Furthermore, if the billet was only decarburised at the surface, it would not be possible to shape through hammering.

A further possibility is that cast iron is melted and cast into moulds to make objects, and that the objects are subsequently annealed (Figure 5d). This would be particularly appropriate for mass production, because casting numerous objects from the same moulds will again allow empirical limits to be set on the conditions required for the annealing process to induce decarburisation. Furthermore, the annealing process, which requires temperatures and atmospheres to be maintained for a long time, perhaps days (Liu *et al*. 2022), thereby requiring a lot of charcoal, becomes more economically viable when many objects are annealed together. This seems to be the method used in fifth century BCE China to produce the adzes and hoes excavated at Laohekou (Yangying) in Hubei: these utilitarian objects are composed of white cast iron at the core with a decarburised layer of steel on the surface (Han and Chen 2013; Chen 2014, 221–227). Essentially, the innovation of an annealing process allowed the brittleness of cast iron to be decreased, at least at the surface of objects that needed to sustain impact. However, an important point to recognise here is that surface decarburisation does not render the object malleable; that is, the skills required of the blacksmith would only be those of hammering edges.

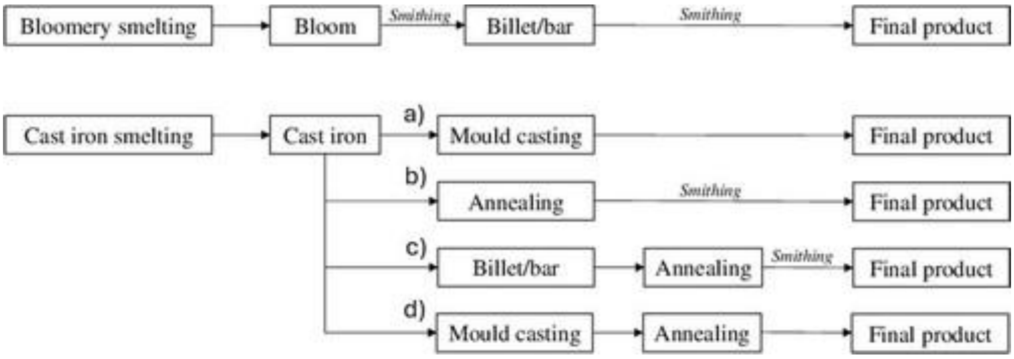


Figure 5: A schematic flow diagram for working with bloomery and cast iron. As mentioned in the text, some of the routes to process cast iron are highly unlikely, particularly for iron that has only been decarburised at the surface.

Making cast iron malleable clearly requires additional infrastructure, time, fuel and workforce compared with making bloomery iron using the direct process. However, irrespective of whether the later technology associated with fining (*c*. third century BCE) had been transmitted from China to Europe along with iron at the time of Pliny, the earlier annealing process (*c*. fifth century BCE) to decarburise iron would have been familiar to anyone who had worked with bronze in the West from the Bronze Age; that is, forging of bronze requires annealing throughout the forming processes to prevent cracking (Zhang *et al*. 2024). In fact, annealing through melting to smelting (Craddock 1995, 122–137) is potentially the trajectory for the inception of metallurgy, as native copper was generally hammered and annealed at a few hundred degrees Celsius, long before temperatures were attained that could melt the metal (the melting point of copper is 1084 °C) or smelt copper ore (at around 900 °C).

Malleablising cast iron through annealing would therefore appear not to have required any more technical skills than for bronze. However, control over the annealing atmosphere is more critical for iron than for copper, because an oxygen-rich atmosphere will readily oxidise iron. Nonetheless, knowledge and experience of annealing would suggest that any cast iron produced in a bloomery furnace in either China or the West could have been annealed. This, again, leads to the question: *Why did China utilise this brittle material, but the West throw it back into the furnace?*

4. To Adopt Bloomery or Cast Iron?

Both China and the West had the knowledge and expertise to make cast iron, and the technology to anneal cast iron to make it malleable. If it were not differences in the technological capital that caused the West to adopt bloomery iron and China to adopt cast iron, other reasons must be found to explain their divergent approaches. We will now examine the social and political contexts in each region from which iron emerged, and the applications that they demanded from iron.

4.1 Prestige Applications of Iron in China and the West

The application of iron in both China and the West was initially for prestige objects, made from meteoritic iron, such as the fourteenth-century BCE gold and iron dagger from the tomb of Tutankhamun (Comelli *et al*. 2016), and later bloomery iron (Wood and Liu 2025b).

Early iron objects in the West at the start of the Greek Dark Ages (*c*. twelfth–eighth centuries BCE) are relatively simple: iron rings, and short iron knives (Collis 1984, 34). Iron objects in cemeteries in Perati (*c*. twelfth century BCE), southern Greece, which turn up in the decades after the Bronze Age collapse (*c*. 1200 BCE), indicate they were bloomery iron; that is, two iron knives were found to have low concentrations of nickel, thereby suggesting that they were not meteoritic iron (Pleiner 2000, 11). Some of these knives, which have bronze and iron rivets, suggest a possible Cypriot origin (Collis 1984, 34). Iron brooches (basically, an arc of iron) and rings are found in Athens in sub-Mycenaean contexts, around a century after the collapse. Similar iron objects have been recovered in the subsequent proto-geometric period (*c*. 1050–900 BCE) (Palermo 2018, tables 2–5). Further west, iron objects have been recovered in Iberia that precede the beginning of the Iberian Iron Age, *c*. eighth century BCE (Armada and Grau-Mira 2018, 305–344), which has significant implications regarding movements across the Mediterranean in the twelfth–tenth centuries BCE (for alternative positions to those of Gilboa and colleagues, such as Eshel *et al*. 2024 regarding early western ventures from the East Mediterranean, see Zorea 2018; 2020; Wood *et al*. 2019; 2020; Bell and Wood 2024). The first iron objects in Iberia date to the second half of the twelfth century BCE until *c*. 1000 BCE (Álvarez Sanchís *et al*. 2016, 151). In central Portugal (Beiras Region), knives appear in places such as Monte do Trigo, Beijás, Moreirinha and Monte do Frade, dated to the twelfth–tenth centuries BCE (Vilaça 2006). Fourteen knives, which have parallels in Cyprus at around 1050 BCE (Torres Ortiz 2008), and four saws from these Portuguese sites, are from iron that is 'soft' and could not compete with a 'good' bronze (Mederos Martín 2008, 63–64). In Alicante, the Villena treasure hoard includes an iron bracelet and other pieces that can be dated prior to 1100 BCE and were possibly hidden around the thirteenth–twelfth centuries BCE (Hernández Pérez *et al*. 2014 , 593–607), again exhibiting parallels with Cypriot expertise (Ruiz-Gálvez Priego 1992; 1993; 2014, 196–214).

Essentially, early smelted iron was used for prestige objects in the West, some of which travelled. More significantly, it appears that, even when objects such as knives and saws appear in the archaeological record at locations distant to where they were made, their mechanical properties are inferior to bronze.

In central China (Figure 6) later in the first millennium BCE, the earliest finds of bloomery iron objects (*c*. eighth century BCE) overlap with meteoritic iron both in time and space, namely at the *Guo* state cemetery in Sanmenxia city, Henan province. In this cemetery, in addition to the three meteoritic iron artefacts, analyses of another three iron weapons (a sword with an iron handle, a dagger-axe with an iron blade, and an iron spear with a bronze handle) all suggest that the iron derived from a bloomery smelting process (Han *et al*. 1999). This is one of the sites where bronze was cast around bloomery iron, perhaps continuing a tradition that had started earlier with meteoritic iron objects (Chen *et al*. 2018). The different types of iron unearthed here could indicate an indigenous transition to bloomery iron production, as there was presumably insufficient meteoritic iron to meet their needs.

From the eighth century BCE onwards, more bloomery iron products are found in multiple locations across central China as well as the surrounding areas (Figure 6). The majority of finds are bimetallic and mostly unearthed from burials located in Gansu, Ningxia and Shaanxi provinces, located to the north and northwest of central China. For instance, in tomb no. 2 in Yimen, Shaanxi province, a total of 24 iron swords and knives with gold handles were unearthed (Tian and Lei 1993; Baoji Municipal Institute of Archaeology 2016). The burial itself was dated to the fifth century BCE, with a mixture of both the Qin and nomadic cultural elements (Zhang 1993; Zhao 1997). Analysis carried out on one of the swords showed a ferritic matrix with typical embedded bloomery slag inclusions (Bai 1994).

Similar results, also from the Spring and Autumn period, were obtained from four iron swords with bronze handles unearthed from different locations in Ningxia (Han 1998), one iron sword with a bronze handle unearthed from tomb no. 1 in Lingtai, Gansu province (Liu and Zhu 1981), and one bronze knife with an iron blade and a bronze dagger-axe with an iron blade unearthed from tomb no. 27 in Liangdaicun, Shaanxi province (Chen *et al*. 2009). In addition to being bimetallic with bronze cast onto iron blades, these objects exhibit similar archaeological contexts. For example, tomb no. 1 in Lingtai, Gansu, tomb no. 2 in Yimen and tomb no. 27 in Liangdaicun are large-scale burials belonging to social elites. Furthermore, these burials contain certain cultural elements related to nomadic civilisations (Liu and Zhu 1981; Chen *et al*. 2009), such as those that inhabited the Eurasian Steppe.

Overall, there appears to be cultural–processual parallels between early iron use in China and the West, which suggests a common, perhaps evolutionary, trajectory. Essentially, after the adoption of the bloomery furnace, iron was used as a prestige material, first in the West and later in China.

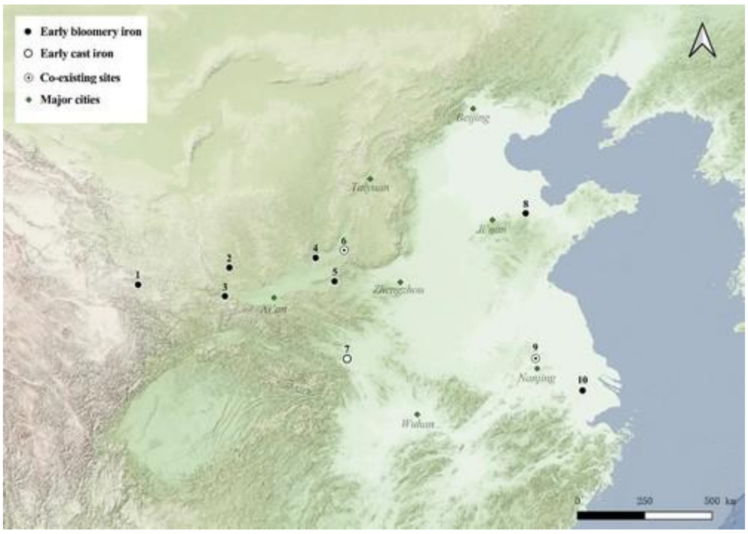


Figure 6: The locations of early bloomery iron and cast iron pre-dating the Warring States period (i.e before 475 BCE). Note that this is not a complete list of iron finds in China from this period, but a summary of those that have undergone scientific examination (Wood and Liu 2025b).
1. Mogou, Gansu. 2. Lingtai, Gansu. 3. Yimen, Shaanxi. 4. Liangdaicun, Shaanxi. 5. Sanmenxia, Henan. 6. Qucun, Shanxi. 7. Yangying, Hubei. 8. Linzi, Shandong. 9. Liuhe, Jiangsu. 10. Wuxian, Jiangsu.

4.2 Socio-political Contexts of China and the West in their EIAs

Iron in both the West and China does not appear to remain a prestige metal for long. It is almost as if there is recognition in both regions, but in different periods, that iron's potential had yet to be fully realised. We propose that it is how iron's potential is realised *after* being predominantly a prestige material in China and the West that the divergence between the two regions occurs, and we can begin to answer the question *Why did the West not develop cast iron technology earlier than China?*

In the West, iron first appears at the beginning of the so-called Greek Dark Age, a time between the Bronze Age collapse (*c*. 1200 BCE) and the emergence of Archaic Greece (*c*. eighth century BCE), when settlements became fewer and smaller, pottery became stylistically simpler, evidence of writing, monumental construction and figurative art disappeared, graves became noticeably poorer, and the population declined (Collis 1984, 38–45; Dickinson 2006, 76–77, 238; Osborne 2009, 74, fig. 19b; Celestino and López-Ruiz 2016, 134; Papadopoulos 2016). Moreover, the diplomatic and trade relation networks of Assyria, Babylonia, Egypt, the Hittite Empire, and the Kingdom of Mittani, that is, the 'Club of Great Powers' (Van de Mieroop 2010, 188), were severed. That bronze was dependent on functioning trade networks, with tin probably deriving from distant locations to where bronze was made (Muhly 1985; Pigott 2011, 273–291; Lehner and Yener 2014, 529–557; Berger *et al*. 2019; Powell *et al*. 2022; Williams *et al*. 2025), suggests that the collapse of long-distance trade would have made bronze difficult to manufacture.

Regardless of where iron was first smelted (i.e. Anatolia, the East Mediterranean, Mesopotamia, the Caucasus, etc.), or why it was adopted much later in Egypt, with the inevitable implications for the origins of iron in Africa, its adoption was clearly beneficial to the individuals and societies that mastered the process. Better properties than existing materials (e.g. bronze) have been proposed as the impetus for innovation in iron technologies (Muhly 2003) to replace those of bronze (Yahalom-Mack *et al*. 2017). The ubiquity of iron ores (e.g. compared to copper ores) is often coupled with these properties to advance the view that it was a more 'democratic' metal (again, compared to bronze) (Childe 1951, 180; Hooke 2000). Potential shortages in the supplies of tin and copper because of, and resulting in, breakdowns in trade routes, have raised the possibility that local smiths needed to exploit a new metal to make their tools (Maddin *et al*. 1977).

Shortage models, however, are not particularly well-supported by the archaeology, with continuations and sometimes increases in copper production, such as that suggested in thirteenth- and twelfth-century BCE Cyprus (Muhly 1992), making it difficult to advocate for the rise of iron being caused solely by a dearth of copper. The other side of the same coin, however, recognises that iron ore was more ubiquitous than copper ore, and that it might have also been more attractive than copper/bronze to newly formed polities, especially those that emerged after the twelfth-century BCE collapse of the LBA palace system in the East Mediterranean, because it allowed smaller states to decrease their reliance on foreign trade (Mirau 1997). For example, the Levant saw a decentralisation of political power, in which local elites were less closely tied with regional empires, allowing them to take advantage of new, locally available, resources (Mirau 1997). This view would suggest that the adoption of iron is perhaps better explained through changes in society and demography. That is:

- iron may not have always been a replacement for other materials (such as bronze) but was required, at least at first, to produce prestige objects that could be traded
- even though a small polity might adopt iron (perhaps to reduce its reliance on long-distance trade), this does not necessarily mean that larger, highly interdependent, states would have also allocated part of their workforce to iron production.

However, the breakdown of the palatial system, the fall of the major Mediterranean civilizations around 1200 BCE, would have discharged not only merchants but also skilled craftsmen (Zaccagnini 1983). The beginning of the Iron Age in the West might therefore have had to contend with not only disruptions to long-distance trade such as that required for tin, but also the formation of polities that may have acquired metal workers from other places but not the connections to make bronze.

In effect, the would-be blacksmiths of the Iron Age, potentially emerging from the collapse of societies (including Minoan Crete, Mycenaean Greece, the Hittite Empire, Mittani, Assyria, and Kassite Babylonia: basically most of the Old World apart from Egypt) that had controlled the production and movement of bronze, acquired new skills to work with a new metal, a metal that they could not melt and cast, namely bloomery iron, to become specialists for the polities that emerged after the collapse. Essentially, bloomery iron in the West may have become the metal of choice because of social, economic and political changes that suddenly created a situation reliant on possibly estranged individuals who were able to smelt and forge iron into useful objects without the need for external contacts. It must be also noted that this potential form of local resilience characterised the technology that made its way across the Eurasian Steppe into China during the Western Zhou dynasty (*c*. 1046–771 BCE) in the early first millennium BCE.

To some extent this narrative is evidenced by iron finds. The West began to make iron weapons and tools in the centuries after the Bronze Age collapse. The proto-geometric period in Greece (*c*. 1050–900 BCE, a period with perhaps minimal external contacts; Collis 1984, 35–36) is around the time when iron is first used for full-scale weapons in the West, such as the flange-hilted iron sword from a warrior burial at Tiryns, datable to the eleventh century BCE (Palermo 2018, table 6). Bronze is extremely rare. Deliberate carburisation seems evident in a Cypriot dirk from the eleventh century BCE, shaped similarly to a contemporary bronze weapon (Craddock 1995, 258). However, iron in settlement contexts is missing in Greece and the Aegean (Mokrišová and Verčík 2022). Iron objects in cemeteries at Lefkandi on the island of Euboea, and in the sub-Mycenaean (*c*. 1100–1050 BCE) cemeteries in Attica (Snodgrass 2000, 231–236; Papadopoulos and Smithson 2017, 924), perhaps exemplify an emerging EIA elite who desired ownership of iron objects; that is, although the skills of the blacksmith must have developed to make these objects, their applications were aimed at the high-status market. This view subscribes to Sherratt's (1993, 85) assessment of iron in the East Mediterranean, where she notes that 'From the 12th century on, iron in general moved from the status of an epiphenomenal preciosity, through that of a supplement, to that of a partial but equally effective base metal substitute for bronze'. In fact, the twelfth-century BCE Cypriot knives, which are not lavish but probably appealed within the value terms associated with iron of the LBA, suggest 'a status-enhancing novelty' (Sherratt 1993, 68). In effect, these iron blades *might* work better than bronze blades, and therefore *may* suggest a first venture in utilitarian iron.

Iron objects found in Cyprus, however, can perhaps be considered a petri dish regarding iron, as iron appeared rather abruptly. Table 2 (adapted from Palermo 2018, table 16) shows that iron objects are exceedingly rare prior to 1200 BCE. Between 1200 and 1050 BCE, iron appears to have several applications: ornaments are prestige and, as discussed above, many knives may also fall into this category. Only three tools (a sickle, a chisel and a blade) are dated between 1200 and 1100 BCE, with the remaining tools attributed to a wider chronological range (1200–1050 BCE) (Palermo 2018, table 8). Weapons (spear- and arrowheads) are absent in this period. Iron is used for weapons between 1050 BCE and 900 BCE, whereas numbers of ornaments decrease.

Table 2: Categorised iron objects from Cyprus (adapted from Palermo 2018, table 16).

Late Cypriot (LC)/Cypro-Geometric (CG) periods	Knives	Daggers	Swords	Weapons	Tools	Ornaments	Other	Total/period
LC II (1450–1200 BCE)	0	0	0	0	0	0	2	2
LC III (1200–1050 BCE)	40	7	2	0	17	14	8	88
CG I (1050–950 BCE)	42	5	6	19	36	13	3	124
CG II (950–900 BCE)	45	1	4	19	9	2	2	82
CG I-III (1050–750 BCE)	4	0	1	0	3	0	0	8
Total objects	131	13	13	38	65	29	15	304

Note: 5 knives and 1 ornamental spatula represented by handles only.

Prestige knives are much less common in eleventh–tenth-century BCE contexts in Cyprus, with iron also taking on much more obvious practical applications; that is, later knives often have wooden handles, probably an indication of their utilitarian function (Palermo 2018). Sherratt (1993, 71) notes that the sequences of tombs from Palaepaphos Skales 'consist of knives, daggers and swords and a variety of relatively uncomplicated functional tools and structural rods or nails – artefacts for which iron by now seems to present proven practical advantages'. If these observations can be taken as a proxy for the trajectory of iron adoption in Cyprus, this might suggest a period of experimentation of between one and two centuries after the emergence of bloomery iron, before utilitarian iron objects were produced. The presence of tools during LC III perhaps undermines this timeframe. However, tools appear at centres that had their metallurgical facilities intensified in LC IIIA (Sherratt 1998, 300), possibly suggesting that there was sufficient iron in these locations to be applied to a range of domestic and industrial objects from the very beginning of LC III.

There will always be debate over what constitutes utilitarian iron. It is also difficult to determine from often heavily corroded objects their degrees of carburisation, and therefore their hardnesses, to differentiate utilitarian from prestige iron. At tenth-century BCE Lydia in Anatolia, however, tools and metal fixtures attest an early use of iron for utilitarian purposes and its diversity within a household context (Ramage *et al.* 2021, 271). Interestingly, the curved sickle blade found in the 'Lydian trench' was made of pure unhardened iron (Waldbaum 1983, 181) and an adze had a very heterogeneous microstructure with slag inclusions. However, the adze exhibited traces of layering sheets of carburised and uncarburised bloomery iron, representing, presumably, the piling process mentioned earlier. In effect, local experimentation with hardening for utilitarian objects took place at Sardis in the early first millennium BCE (Waldbaum 1983, 178–180).

It is possible that any newly formed polity would have safeguarded their advantage over their skills to work iron. Whereas prestige iron may have moved freely towards the end of the second millennium BCE (such as the Hittites supplying other kings with iron, and iron knives travelling to Perati and Iberia, perhaps from Cyprus), the proliferation of high-status functional objects, particularly weapons, was probably more tightly controlled, because trading iron that could be reworked (not remelted) at the hearth might have been detrimental to those that had supplied it. This may account for the generally slow transition to utilitarian objects in many parts of the West. It is for this reason that we differentiate prestige and high-status functional objects in Table 1 and place the start of the West's Iron Age in the eleventh century BCE; we consider the twelfth-century BCE knives from Cyprus as prestige, partly because they appear to be personal ornaments, but also because their inferior properties to contemporary bronzes were perhaps the reason they could travel. In effect, sometime between the twelfth and tenth centuries BCE iron ceased to be prestige, then became functional, but for an elite market, and finally became utilitarian: it is probably difficult to view any material as both high status and utilitarian (Wood and Liu 2025b).

Later bloomery iron finds in the eastern part of central China, including Shanxi (seventh–sixth century BCE), Jiangsu and Shandong (fifth century BCE) provinces, are not bimetallic, nor do they have any decorative characteristics compared with those bloomery objects found further west in China. Essentially, they are neither prestige items nor weapons: bloomery iron was being used to make iron bars, small knives and shovels. Iron swords do not make an appearance in the archaeological record in China until the late Warring States period and possibly later (Wagner 2008, 115–122). The move towards using bloomery iron to produce utilitarian objects in China was potentially the stimulus for the transition from bloomery iron to cast iron. For example, the earliest farming implements found in China (at Laohekou, Hubei, during the late Spring and Autumn period, *c*. sixth–fifth century BCE) were made from decarburised cast iron. In other words, the later utilitarian bloomery iron finds that emerged in China perhaps lend themselves more readily to being cast than forged.

There is a fundamental difference between China and the West at the beginnings of their respective Iron Ages that potentially greatly influenced China's adoption of cast iron. Cast iron production in China was *not* in competition with bronze because its primary application was for agricultural implements that had not previously been made in metal (Bai 1985; 1989). In fact, the importance of iron as the metal of choice in China in the sixth–fifth centuries BCE is perhaps best appreciated when it is noted that the Chinese Bronze Age was *not* accompanied by a significant use of metal farming implements, irrigation networks, or the use of the plough and draft animals. In fact, the breakthrough in agricultural technology in China does not appear to arrive until around 600–500 BCE, during the second half of the Spring and Autumn period of the Eastern Zhou (*c*. 770–476 BCE), when cast iron began to be used widely for agricultural implements (Chang 1986 , 364). The Chinese iron-shared ox-drawn plough, for example, emerged in about 500 BCE (Bray 1978).

In China, the drive for iron tools that could be used for agriculture probably stemmed from territorial expansion. This is best evidenced in contexts that led up to unification under the Qin in the third century BCE, where pastoralists and riders from the Steppe clashed with forces of the central states moving north (e.g. into the kingdom of Zhongshan) in the late fourth century BCE. Iron agricultural tools allowed farming communities to move into less favourable regions to clear scrub and trees (Rawson 2023, 269, 286). However, even during the Spring and Autumn period (*c*. 770–476 BCE), early counties (*xian*) were all located in strategically important bordering areas, including virgin land in newly conquered territories that the state was eager to open. The introduction of iron tools helped accelerate this process (Feng 2013, 166–170, box 8.1). Moreover, from the Warring States onwards (475–221 BCE), there is evidence of cast iron production in Henan, Hebei and possibly Shaanxi and Shandong (Wagner 2008, 201, table 2). In effect, although there may have been a move towards utilitarian objects with bloomery iron production in China (i.e. the iron bars, small knives and shovels from the seventh–fifth centuries BCE mentioned earlier), it is only with mass production of cast iron for farming that political directives of territorial expansion of the central states could have been implemented.

The scaling-up of cast iron use in China had deleterious effects on bloomery iron production, particularly its use for prestige objects. Specifically, the application of cast iron to make practical objects in China relegated iron from being a prestige metal used for high-status objects to a utilitarian metal, thereby stymieing the adoption of the bloomery iron process in favour of mass-produced cast iron delivered by the blast furnace (Wood and Liu 2025b). In fact, bloomery iron production almost disappears after the fifth century BCE and was no longer sanctioned after the imposition of the Han imperial monopoly (Wagner 2008, 246).

In effect, China found a new application for metal, and chose iron, specifically cast iron. The iron required for farming implements needed only to be tailored for this limited purpose and so could be mass produced. Annealing, although time-consuming, and thereby using a lot of fuel, was only required for the surface of these utilitarian implements, and forging the edges of implements (Liu *et al*. 2023) would not have needed the same level of skill as making weapons and tools from bloomery iron at the hearth; unlike the West, where iron initially catered for an elite market, the cast iron industry in China was developed with a view to mass production. State control and centralisation of cast iron production in China towards the end of the first millennium BCE, which was able to manufacture iron objects of various mechanical strengths at different production costs using a range of iron–carbon alloys from a cast iron precursor (Liu *et al*. 2023), reinforced the trajectory of China to use solely cast iron.

4.3 Access to Technology to Produce Cast Iron

We have already discounted any major differences in the technological capital that could have led the West to adopt bloomery iron and China to adopt cast iron. However, we noted that blacksmiths in the EIA in the West were perhaps working independently of bronze workers, and that, even after iron became stronger and harder, it appears to have been customised for an emerging EIA elite. Essentially, the skills of the blacksmiths in the West were to tailor the iron to each high-status application. Conversely, China, at least initially, required mass-produced iron for agricultural expansion, which we propose required much greater access to other technologies but perhaps less individual skill. This is not to demean the skills required of cast iron workers in China, but to recognise that the set of skills required to make cast iron would have required a division of labour. We propose that these divisions required *access* to the skills and techniques of the bronze and pottery industries:

- Cast iron needed to be melted

The first Chinese text that mentions melted iron (Zuo Qiuming's Commentary on Spring and Autumn Annals) is dated to 513 BCE: a casting of a cauldron (Yang 1990, 1504). The ironworks of the Early Han period at Tieshenggou includes a cupola furnace (Needham 1964) in addition to eight blast furnaces, a smithy hearth, 16 kilns, one fining hearth and the reverberatory furnace (Wagner 2008, 201–209, table 2, item 8, section 5). Wagner also identifies cupola furnaces at Han ironworks in Xian (Shaanxi), Guxingzhen (Henan) and Wafangzhuang (Henan) (Wagner 2008, 237). Nine were found at Wafangzhuang and, based on this material, Chinese metallurgists and archaeologists have produced a reconstruction (Figure 4b). The presence of cupola furnaces demonstrates the association that is often cited between iron and bronze.

- Molten cast iron needed to be cast into ceramic moulds before annealing in kilns.

The Chinese word to exert a beneficial influence on a person's mind and character (taoye陶冶) relates to the firing of pottery and the processing of metal; that is, tao陶 (pottery making) and ye冶 (metallurgy), potentially suggest a symbiotic relationship. Both China and the West would have been able to achieve the temperatures required for annealing cast iron (700 °C–1000 °C). However, China had produced kilns and reverberatory furnaces for its pottery industry that also maintained low oxidative atmospheres. The pottery firing techniques developed before 2000 BCE had kiln rooms and fire chambers, allowing the temperature to rise to 1100 °C using natural wind. The innovation of a chimney on the pottery kiln in the ninth–eighth century BCE enabled higher temperatures in the firing chamber, allowing pottery to be glazed; for example, firing reached 1200 °C at the Zhangjiapo site in Shaanxi province (Qian and Huang 2021) and therefore potentially relates to the origins of porcelain (Zhou *et al*. 1960). In other words, Chinese potters were capable of maintaining tight control of both temperature and atmosphere in their kilns, an important consideration to prevent iron oxidation while annealing to decarburise cast iron.

This is not to say that the West did not develop kilns with reducing atmospheres (in fact any closed container filled with charcoal could be used), but it is interesting to note that kilns are often found in excavations of ancient Chinese ironworks. Although some of these were clearly used for firing ceramic moulds, the absence of ceramics that could have been used as 'annealing pots' might suggest that reverberatory furnaces, such as that excavated at the Tieshenggou ironworks site in Henan province (second century

BCE–early first century CE), were perhaps used to anneal cast iron: castings were packed in iron oxide in a large sandstone chest (Wagner 2008, 169). The reverberatory furnace for the iron industry was potentially an advancement on the kilns that are found at cast iron production sites from the Warring States period (Wagner 2008, 201–209, table 2, section 5), and therefore the presence of kilns in association with ironworking suggests mass production of annealed iron from a cast iron precursor.

Essentially, the cast iron industry required expertise from those making pottery (for annealing kilns and ceramic moulds) and bronze (for the cupola furnace and the skills for casting molten metal), as well as from those who could run bloomery furnaces and its subsequent adaptation, the blast furnace, to provide the raw material required to make cast iron objects. This leads to the following hypothesis.

Cast iron derived from the bloomery furnace (and later the blast furnace) was melted in cupola furnaces that had been developed by the bronze industry to cast in moulds, to make objects that were annealed in kilns that had been developed by the pottery industry. It is this association of technologies and skills that led to the *cast iron industry* in China.

We believe that cast iron production *required* successful relationships between skilled workers and their technologies for it to be adopted, and China had access to the technologies from functioning bronze and pottery industries. This perhaps provides an explanation as to why cast iron emerged in the Central Plains rather than in Xinjiang in northwest China, despite the suggestion of earlier bloomery production in Xinjiang during the tenth century BCE (Chen 1990; Han 2018): Xinjiang, without a flourishing bronze industry, did not transition from bloomery iron to cast iron.

In contrast to the Spring and Autumn period in China, the proliferation of iron in the West that resulted in its Iron Age occurred at a time when societies were collapsing. Irrespective of whether there was a causal relationship between the Bronze Age collapse and the rise of iron, or whether bronze was still being produced in some locations that could have led to the development of a Western version of the cupola furnace, or even if pottery kilns in the West could control the temperatures and atmospheres required to decarburise cast iron as well as those in China, the *connections* between these industries, bronze, pottery and iron, which were utilised successfully by a nascent Chinese cast iron industry, were damaged in the West because of the Bronze Age collapse; the Dark Age was dark because communications had been disrupted across a vast region. In effect, iron in the West emerged from collapsed societies and the formation of new polities, where individuals, possibly migrants (Zaccagnini 1983), became specialists who developed and utilised their skills to exploit bloomery iron, because the connections required to capitalise on the cast iron produced in the bloomery furnace were no longer in place.

The question *Why did China utilise this brittle material, but the West throw it back into the furnace?* is therefore answered by proposing that it was easier for iron smelters in the West to throw cast iron back into the bloomery furnace as part of the next charge than to develop and share techniques, build an infrastructure, and mobilise a workforce that could feed a fuel-hungry industry across a fragmented region. It is perhaps not so surprising that the fragmentation that would have affected the trade networks of the West to supply the raw materials to make bronze also provided the impetus to utilise bloomery iron instead of cast iron, because processing bloomery iron minimised the need for external contacts and advanced local resilience.

Conversely, China began to develop its cast iron industry during the Spring and Autumn period (*c*. 770–476 BCE), which had a culture of innovation not only for the development of the cast iron industry but also for the indigenous production of other metals, such as silver (Wood and Liu 2025b), which had crossed the Eurasian Steppe, as well as having functioning bronze and pottery industries. Essentially, the answer to the question *Why did the West not develop cast iron technology earlier than China?* rests on the social and political contexts of each region at the time when iron first emerged, rather than any differences in their technological capital. The main decisions proposed are summarised in the flow diagram in Figure 7, which shows the divergent paths of iron adoption, with the Chinese experimenting with furnaces to favour cast iron over bloomery iron to be used for mass production, and blacksmiths in the West experimenting with the properties of bloomery iron at the hearth to compete with bronze to make high-status, but functional, items for the emerging EIA elite around the East Mediterranean.

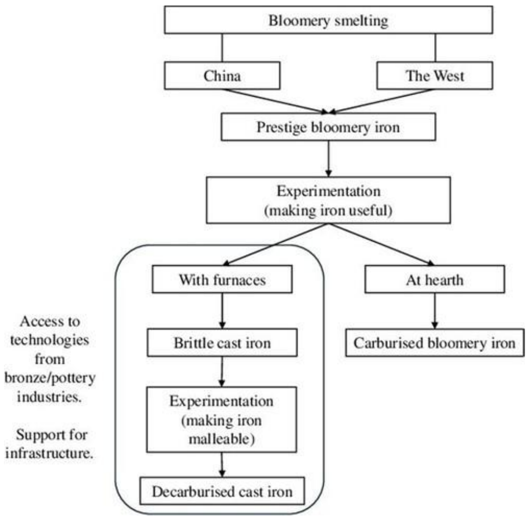


Figure 7: A flow diagram that shows the diverging trajectories of the adoption of iron between China and the West.

5. To Accept or Reject?

The related, but different, question *Why did China develop cast iron technology 2000 years before the West?* remains. Presumably, after recovering from the Bronze Age collapse and emerging from the Greek Dark Age, the West could have started to utilise cast iron produced in its bloomery furnaces and develop similar technologies to those in China, technologies that were to sustain the cast iron industry in China from the sixth–fifth centuries BCE to modern times.

This question can be approached by invoking the concept of 'habitus' (Bourdieu 1977, 72–95), which can be loosely described as how individuals self-regulate their own behaviour to fit social expectations. The arenas for action, or 'fields', where individuals move, socialise and position themselves, encompass power relations that determine the structure of social positions within it. Individuals are driven to play the game of their own making and secure their field (Maton 2008; Bietti 2023).

Essentially, the blacksmith communities in the West may have safeguarded, perhaps unintentionally, their cultural capital by protecting their way of producing iron: the introduction of cast iron technology would have threatened the social advantage of their field. The status quo for the blacksmith's habitus, which comes with its own set of knowledge and skills within the field of the blacksmith community, could be maintained by throwing any cast iron made in the bloomery furnace back into the furnace with the next charge. Furthermore, it would have been beneficial to adapt furnaces to reduce the amount of cast iron produced and increase the amount of bloomery iron, because bloomery iron relied on the skills and expertise of a specific group of individuals. By the same rationale, cast iron technology from outsiders, such as anyone with knowledge and experience of Chinese cast iron technology at the time of Pliny, would not have been readily accepted, not only because it can be difficult to form a new habitus, but also because it can be challenging to accept one. In effect, blacksmiths were driven to secure their field, and their status within it, by perpetuating inequality, with blacksmith communities in the West potentially protecting their ways of life from the EIA onwards through various devices, such as apprenticeships and guilds, that could respond to different social and political stimuli, until the European industrial revolution in the late second millennium CE. In fact, since the Romans *were* importing quite a lot of material from China (particularly silk), it seems surprising that cast iron technology was not adopted by the Roman Empire, especially after Pliny's glowing endorsement of its quality, without invoking some kind of protectionism. Of course, this protectionist argument applies equally to the Chinese, who may have wanted their products, but not their process of making cast iron malleable, to be disseminated to other regions (although, as mentioned above, the West had the technology to malleablise cast iron by annealing).

However, there may be other issues at play. Although decarburised cast iron may have been technically superior to bloomery iron (e.g. with fewer slag inclusions), it must be noted that Chinese iron goods do not seem to have displaced local bloomery iron products in places like Japan, Korea (Park and Rehren 2011; Park 2012) and South-East Asia (Huang 2013; Zou *et al*. 2022), perhaps suggesting that transport costs outweighed any technical advantage offered by products made from cast iron. Essentially, even though Pliny says that the highest quality iron was from China, it clearly was not of sufficiently high quality to replace bloomery iron products of the Roman world, perhaps also because of transport costs, which presumably would have been higher than for markets closer to China.

The introduction of new technology is also a difficult sell unless it can be shown to be technically and economically advantageous (Rogers 1962; Schiffer 2004). Mass production reduces costs, and poorer ores can be used to produce cast iron than bloomery iron. However, there is also the issue of variability. Because the two-stage production process required to make cast iron malleable requires more fuel (as well as more time, workforce and infrastructure), there must have been pressure to minimise annealing times, and thereby the degree of decarburisation; that is, the final quality of the product was potentially influenced by fuel and labour shortages.

Moreover, the Chinese recognised that annealing was not cost-effective. It had been used for agricultural implements when only the surface needed to be decarburised. However, by the third century BCE, decarburisation was being conducted using the fining technique, an exothermic process that involves remelting lumps of cast iron in the oxidising atmosphere of an open hearth to remove the carbon (Han and Ko 2007, 612; Liu *et al*. 2019). This process, however, results in the introduction of slag inclusions that affect not only the mechanical properties of the iron produced but also its durability (Bowman *et al*. 1984). Essentially, even though annealing was still used for high-quality objects (Liu *et al*. 2022) (presumably, for these objects, complete decarburisation was cost-effective), cast iron began to be decarburised using the fining process that affected the quality and potentially introduced unacceptable variability into the final product. This was the iron that failed to displace bloomery iron in locations outside China in East Asia, Southeast Asia and the Roman world.

The answer to the question *Why did China develop cast iron technology 2000 years before the West?* may, again, not be related to differences in technological capital between each region, but the fact that the bloomery iron industries already in place in the West were run by specialist blacksmiths who had a vested interest in improving and tailoring their skills to protect their livelihoods. By the same rationale, the transition from bloomery iron to cast iron production in China may have been adopted without much opposition from blacksmiths, because iron production was most likely developed within the bronze industry rather than independent of it; that is, blacksmiths in China had a different habitus and field, which meant they were perhaps less invested in maintaining the status quo than their counterparts in the West.

Cast iron was eventually adopted in the West. Although the western blast furnace may have had an independent origin, its introduction in Europe came at a time when contact between East and West was well established. All that was needed was an appreciation of the usefulness of cast iron (Tylecote 1992, 76–77). Whether for chisels for mining in the fifth–sixth centuries CE (Cornacchia *et al*. 2014), or for guns, iron shot and cannonballs in the fifteenth century CE (Tylecote 1992, 77; Gruttadauria *et al*. 2022), the West found applications that were better served by using cast iron than bloomery iron, applications that probably capitalised on the better iron yields that cast iron smelting could provide. This is not to say that bloomery iron was completely supplanted by cast iron as soon as the West decided to adopt it (see Tylecote 1992, 95–108). Ironically, when the West started to use the blast furnace, old bloomery slag was thrown back into the furnace as a flux (Tylecote 1962, 304), just as cast iron and iron-rich debris had once been thrown back into the furnace with the next charge of the bloomery furnace. However, Agricola, in his *De Re Metallica*, showed a mechanical hammer for working the bloom (Agricola 1556, trans. Hoover and Hoover 1950, 422), which could indicate that the habitus associated with the traditional western blacksmith was in flux from the post-medieval period. Mechanisation perhaps made the benefits of utilising cast iron more attractive for those investing in infrastructure to produce iron on a larger scale, in a similar fashion to how cast iron had been adopted 2000 years previously by the state in China practising division of labour. The position of state iron workers in China was also in flux in the mid-second millennium CE; cast iron remained dominant, but eventually China removed its monopoly on iron production, within a climate of civil unrest and potential invasions, in favour of free enterprise during the early Qing dynasty (Wood and Liu 2025a).

6. No Diversity (of Iron) in the Workplace

There appears to be no difference in technological capital between the West and China when it came to making iron. Both had the technology to produce bloomery and cast iron at the start of their respective Iron Ages. Furthermore, both regions had the skills to forge bloomery iron into prestige objects, and the technologies to anneal cast iron to make it malleable. However, despite inventing the bloomery furnace, the West did not develop a cast iron industry before China or adopt the process until the modern historical period. We propose that the Bronze Age collapse, which disrupted the trade networks of the West that had supplied the raw materials to make bronze, also provided the impetus to utilise bloomery iron instead of cast iron, because working with bloomery iron minimised the need for external contacts and potentially increased local resilience. Basically, iron–carbon alloys do not require the procurement of another metal. We further propose that the West's trajectory to adopt bloomery iron was fixed through its reliance on specialists (blacksmiths) who could work independently of the bronze and pottery industries in the fragmented socio-political context of the so-called Greek Dark Age. With a vested interest to improve and hone skills that protected their livelihoods, blacksmiths in the West entered their Iron Age by tailoring objects to cater for an emerging EIA elite, and managed to maintain and protect this social advantage until the adoption of the blast furnace in the second millennium CE.

The bloomery process made its way into China in the first millennium BCE, which eventually seeded the production of cast iron. Without the introduction of the bloomery furnace there would have been no cast iron industry. However, China developed a cast iron industry before the West because its demand for utilitarian iron (and, therefore, its Iron Age) started during a period of innovation. The Spring and Autumn period had flourishing bronze and pottery industries that provided technologies and skills that could support the socio-political directives of agricultural expansion utilising cast iron, by producing farming implements that had not previously been made in metal. Although developments in the decarburisation process further advanced the cast iron industry, cast iron production does not appear to have reached beyond China until at least the mid-first millennium CE, and perhaps later. Whether this was because bloomery iron operations in the West, as well as regions near China, suppressed the introduction of cast iron, or because the costs of setting up cast iron industries or importing cast iron from China were prohibitively high, it seems that Pliny's glowing endorsement of Chinese iron is merely a historical footnote. Nonetheless, cast iron could satisfy the Chinese domestic market.

Without the connections between the iron, bronze and pottery industries, China would have probably taken a similar trajectory to the West and continued producing bloomery iron. It is tempting, therefore, to speculate that, although the bloomery furnace can produce both bloomery iron and cast iron, socio-political factors will always favour one *industry* over the other; that is, cast iron and bloomery iron production might be mutually exclusive. The blacksmith working with bloomery iron at the hearth requires more individual expertise but will also have greater control over the final product than an ironworker in the cast iron industry. However, the introduction of mass-produced cast iron can make those working with bloomery iron redundant unless blacksmiths secure their social advantage: mass-produced cast iron implements do not require expert blacksmiths. It is perhaps also in the best interest of states, particularly in times of unrest, to have control over materials that can be turned into weapons. The polities that emerged after the Bronze Age collapse in the West may have safeguarded their advantage by restricting the proliferation of functional iron, slowing down the transition to utilitarian applications and, thereby, contributing to delaying the Iron Ages in many parts of the West. In China, producing malleable iron from cast iron required more infrastructure, sharing of technologies and division of labour than working with bloomery iron, which suggests that it was more likely to be initiated by those with socio-economic power. In other words, bloomery iron production remains dominant when cast iron production is suppressed, and cast iron production remains dominant by stifling independent bloomery iron operations that can no longer compete with a state-controlled iron industry and could also threaten the dominance of the state that set up the cast iron industry. It is, therefore, perhaps not so surprising that the Han dynasty imposed an iron production monopoly in 117 BCE that effectively outlawed bloomery iron production until the Qing dynasty.

The fact that the West did not adopt cast iron until the modern historical period suggests that its trajectory for iron had already been set; that is, if the West had not suffered the Bronze Age collapse it might have adopted cast iron for utilitarian objects. How this would have manifested is difficult to say, but it is probably not far-fetched to suggest that the states that controlled bronze production at the end of the Bronze Age in the West would have also controlled iron production and suppressed independent bloomery iron producers who could threaten their dominance. In other words, a centralised iron industry in the West in the EIA would potentially have had the same trajectory of iron adoption as China half a millennium later; the West could have adopted a cast iron industry at state, and perhaps regional, level that would have monopolised iron production. Overall, the decisions made in response to the choice offered by the bloomery furnace between bloomery and cast iron in the West and in China do not appear to have been based on technology per se, but on the technological capital *accessible* in the political and socio-economic circumstances that led up to their respective Iron Ages, setting courses of action that had repercussions for millennia.

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Author Contributions

Y.L. initiated the article and provided detailed comments. J.W. formulated arguments and wrote the text. Both authors reviewed the manuscript.

Data Availability

All data generated or analysed during this study can be found in the works referenced.

Declarations

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