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Coppering the Industrial Revolution

History, Materiality and Culture in the Making of an Ecological Regime

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Abstract

No copper, no Industrial Revolution. Although accountants listed it in the very last position in the table of "value added" per sector in 1831, the British copper industry was essential for the Industrial Revolution, the period of British hegemony over the world-economy. In this article, I use the figure-ground method proposed by Terence K. Hopkins to show that the copper industry played key roles in the ecological regime of the 1700-1840 period, due to its material properties and related historical contingencies and cultural valuations. By focusing in on particular production processes, historical contingencies, and cultural phenomena in which copper played an important and unique role, and then zooming out again to the world-economy as a whole, I show that an Industrial Revolution would not have happened without copper. From sugar production in the Caribbean to textile printing, from the slave trade to the Battle of the Saintes, from the development of the steam engine to gin and rum production, from the telegraph to buckles and buttons, copper was conspicuous. This demonstrates the ecological regime of the period, in which the removal of a single commodity from the picture—i.e., copper—disrupts the whole constellation of relations. This study also shows that a "copper boom" immediately before and at the start of the Industrial Revolution (~1700-1800), instrumental in the British struggle against France for the hegemony over the world-economy, has been overlooked in the literature. Additionally, the article includes a reflection on method.

Keywords: Copper, Industrial revolution, Ecological Regime, Figure-ground movement

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Copper, let us take you
To a furnace where we'll break you
Fire's so big and pretty, you could cry
As a buckle, you could ask me what was wrong with me before -
Did I need the silver to be suitable?
Copper, I have a use for you, it's easy work and it suits you
Dazzled dirty beauty, you must know
Copper is a conductor and makes for decent cooking
Dazzled by your beauty still, you know
Plated or anodized, you even fool a layman's eyes
Presentable though you might be, it's unwise to try to fight me
Copper – you'll never be gold
—Shellac, "Copper" (1998)

Introduction[1]

No copper, no Industrial Revolution. That might sound surprising, as the traditional story tells us that the Industrial Revolution consisted of transformations in the industrial production of textiles, impelled by coal, perhaps with the supporting role of the transformations in the iron industry in Britain.[2] This might seem even more surprising if one looks at the numbers of "value added" for different British industrial sectors in 1831 (See Table 1 below). As the reader can see, copper appears last on the ranked list.

And yet, I intend to demonstrate the key role of copper by highlighting that it was an indispensable commodity of this particular "ecological regime" during the British hegemony over the world-economy, starting around 1750, as well as in the previous struggle for hegemony against France. An ecological regime is understood as the

> durable patterns of governance (formal and informal), technological innovations, class structures, and organizational forms that have sustained and propelled successive phases of world accumulation since the long sixteenth century. At a minimum, these regimes comprise those markets, productive and institutional mechanisms necessary to ensure adequate

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[2] This is the case for the most disparate "schools." See for example Wallerstein (1989:23-6); Deane (1965:87-118); Allen (2009:156-237); Hobsbawm (1968:ch. 3).

> flows of cheap energy, food, raw material, and labor-power to the organizing centers of world accumulation. But the story does not end here. We should also attend to the re/production complexes that consume these surpluses and set in motion new (and contradictory) demands upon the rest of nature. That is to say, the town-country antagonism—overlapping with, but distinct from the core/periphery divide—is the pivotal geographical relation. In this, ecological *regimes* signify the historically stabilized process and conditions of extended accumulation. (Moore 2015:158)

Table 1: value added per sector in British industry, 1831

Sector	Million £	%
Building (*)	26.5	23.5
Cotton	25.3	22.4
Wool	15.9	14.1
Leather	9.8	8.7
Coal	7.9	7.0
Iron	7.6	6.7
Silk	5.8	5.1
Beer	5.2	4.6
Linen	5.0	4.4
Soap	1.2	1.1
Candles	1.2	1.1
Paper	0.8	0.7
Copper	**0.8**	**0.7**

(*) including industrial engineering
Source: Crafts (1985), Table 2.3

I begin with an exposition on the method used, followed by an extensive historical review of the role of copper in different parts and processes of the world-economy. I then provide a synthesis in which the dynamics of the world-system and the methods for its study are reflexively analyzed in light of the results of the study. I argue that the method used fundamentally impacts the ability to uncover systemic relationships.

Remarks on Method

Wallerstein claimed that the Industrial Revolution is often misunderstood "because it starts from the premise that what explains British 'advantage' is a constellation of traits which are absolute when what we need to locate is a constellation of positions which are relational within the framework of a world-economy. It is the world-economy which develops over time and not subunits of it" (1989:33). In order to show the pivotal role of copper in the ecological regime, I use the "figure-ground method" described by Terence Hopkins, combined with a method of experimental history that Millo (1990) called "historical possibilitism."

In Hopkins' words,

> I have in mind the figure-ground movement where if one refocuses, what was figure becomes ground and when one refocuses again, what was ground becomes figure. For us, the figure-ground movement seems to take place centrally between social relations and agencies of action, between role and role relation. I think the methodological directive with which we work is that our acting units or agencies can only be thought of *as formed,* and continually re-formed, by the relations between them. Perversely, we often think of the relations as only going between the end points, the units or the acting agencies, as if the latter made the relations instead of the relations making the units. (Hopkins 1982:149)

Hopkins offers two illustrations: the increasing inequality among the peasantry in Russia as analyzed by Lenin and the concepts of core and periphery in the world-system perspective. In both cases, leaving aside the relational formation of the acting agencies results in reifications: in the first, it prevents one from seeing that the "differentiation" of the Russian peasantry was actually part of the changing social relations, in which part of the peasantry was becoming capitalist, part becoming proletarianized, and part remaining as peasantry proper. In the second case, "core" and "periphery," instead of being actualized in the many ways in which the world division of labor is formed in the world-economy, become reified classificatory terms, and "trade" becomes the only relation between them. In both cases, shifting the focus between part and whole allows one to trace the relations between, and formation of, acting units, thus reconstructing the whole while avoiding reification of the parts.

In this study, following Wallerstein's and Moore's conceptual models and Hopkins' methodological directive, I will successively focus in on particular production processes, technical innovations, and historical events during the Industrial Revolution in which copper, due to its material properties, historical contingencies and cultural meanings, played a significant and unique role. The emphasis, therefore, will not be on capital formation and abstract aggregate variables.[3] Next, I will zoom out to focus on the world-economy as a whole to demonstrate, with a thought experiment, that the world-ecological regime would have been disrupted if copper were removed

[3] For studies on capital formation in the copper trades, which includes disputes over monopoly rights on the Anglesay mines and royalties on Watt's steam engine, see for example Hamilton ([1926] 1967), Harris (1964), Rowe (1953).

from the picture. This procedure combines the figure-ground movement with a method of experimental history that Milo (1990) called "historical possibilitism." The classical application of this was Fogel's (1964) study of the American railroads during the nineteenth century: by removing railroads from the American landscape and assessing the consequences, Fogel challenged the widely held assumption that they were essential for American economic growth.

The demonstration of the role of copper within a constellation of relations with other commodities is at the same time a demonstration of the effective functioning of an ecological *regime*, meaning that those processes represented by the output of different commodities in Table 1 are effectively interwoven in a complex constellation of relations (so that the removal of a single row in Table 1 might effectively disrupt the "whole" represented by the table). In this regard, reducing a regime of accumulation to a single or to a few discrete industrial "sectors," though in some respects analytically useful, could be considered a reification or "violent abstraction," a form of fetishism resulting from an analysis based exclusively on exchange-value (Sayer 1987; Marx [1867] 1990: ch. 1). This is why the figure-ground method fits well with the concept of "ecological regime," as both are based on the relationality between the acting agencies.

It should be noted that I do not employ "incorporating comparison" (McMichael 1991) in this study. Instead, I treat the system as having an objective reality, rather than being merely a "procedure." This is methodologically asserted by assuming that the relations in the world-economy are mediated by value (except in the luxury exchange with the external arena and anti-systemic processes, in which value relations are either not operative or are challenged by social movements), which is already the *result* of a systemic analysis. In Marx's work, this is evident because the chapter that opens the exposition of *Capital* is the result of the investigation of the *Grundrisse*, whose last chapter begins with the words: "this section to be brought forward." (Marx [1867] 1990: ch.1; [1858] 1993: 881-882; Postone 1993: 138-144).[4] In other words, in using the figure-ground method, I assume that the units internal to the world-system are formed and reformed, but the systemic globally structuring category (value) operates throughout the life-span of the capitalist world-economy. This implies that the system's totality is incorporated within the parts; value is the "encompassing" category (real abstraction) of the capitalist world-economy, which gives occasion to a peculiar, historically-specific trajectory (not to be confused with teleology) with differentiated parts.

[4] It should be noted that the chapter on Bastiat and Carey that comes after the chapter on value in the *Grundrisse* is actually the earliest part of the manuscript. See Marx (1993: 883, n. 107).

Zooming in: copper in the parts and processes of the world-economy

The reader should be forewarned that the following subsections will look scattered and maybe disconnected. This is the result of the way in which copper is embedded within the ecological regime prevalent in this historical period, in which its different material properties and associated cultural values, as well as derived historical contingencies, were expressed in a number of manners, circumstances, and geographies. This characteristic makes the role of copper especially suitable for the figure-ground method. The synthesis and implications will be derived when we zoom out, in the next section.

Preparing the Industrial Revolution: Copper in the Atlantic Boom

Eric Williams argued that slave trafficking financed the Industrial Revolution (Williams 1944/1994). More recently, Robin Blackburn expanded the argument to root this "primitive accumulation" in a more general boom of the Atlantic economy, including the economy of the plantations (Blackburn 1997). Would copper have any important role in this boom? Evans and Saunders (2015), though focusing on the period starting in 1830, already suggested the importance of copper to the Atlantic trade from the 1690s. By the end of the seventeenth century, copper mining was declining in Britain. Swedish material dominated the market, mostly destined for the brass industry. However, the situation reversed in the eighteenth century (Hamilton [1926] 1967:277). Deane and Cole note that "while the home consumption of copper and brass seems actually to have fallen from 1725 to 1745, exports were booming." Imports of cotton by weight rose 280% from 1725-1734 to 1765-1774, while copper ore production in Cornwall rose 382% in the same period (1962:51, 58). A more recent assessment by Crafts shows that copper was the industrial sector with the highest output growth rate in 1700-1760, and again in 1760-1770 (1985:23). Ore production in Cornwall and Devon trebled from 5,000 to 15,000 tons in the first period, and doubled again in the second, reaching 30,000. The wars of 1700-1763 seem to have played an important role in the demand for copper (John 1955). Besides, the fact that copper is highly recyclable implied that the stock of copper in use was always growing (Burt 1995).

The domestic brass industry grew enormously from the eighteenth century. Export to East India from 1731 to 1751 amounted to 205 tons per annum on average of cake copper, and from 1751 to 1772 this average was 721 for cake and manufactured copper (Hamilton [1926] 1967:280). Large supplies were also exported to America and to the Continent. Copper vats and boilers were sent to the sugar plantations in the Caribbean for the refining operations. Between 1700 and 1770 the tonnage of copper in British sugar plantations increased from 1,123 to 4,243 tons, which correspond to an annual demand increase from around 100 to around 400 tons per annum (Zahedieh 2013). One should remember that sugar was only partially refined in the colonies (producing muscovado). Further refining was carried out in Bristol, where there were 20 refiners in 1775 (Morgan 1993:97).

From the 1690s, another important source of demand was the domestic brass industry. From 1703 to 1710, 1,483 tons of brass in the form of battery, black latten and metal were still imported, while only 113 tons were exported (mostly re-exports from Holland). But the rapid expansion of brass industry in England and improvement of the quality of brass turned Britain from net importer to net exporter, concentrating on finished products (Hamilton [1926] 1967:284-7).

So far, this only confirms Blackburn's analysis linking the "primitive accumulation" of the Industrial Revolution with a boom in the Atlantic economy. However, after citing the high exports of copper in the period, Blackburn refers to innovations in iron-making, including iron puddling, used only much later (from the 1780s). He adds that "important though it was, the metalworking industry did not witness such a dramatic technical breakthrough as occurred in cotton textiles" in this period (Blackburn 1997:521-2). It might be, though, that Blackburn is underestimating innovations in the copper trades. In Cornish mines, this period represented an important transition from the superficial mining of tin to the deep mining of copper, which entailed higher requirements of capital investment and a more complex division of labor, but in the same region already adapted to mining. Deep mines required the use of gunpowder and drainage. Here starts the history of the steam engine, an icon of the Industrial Revolution. Though the origin of the engines is also related to coal mines, the developers of the models that preceded Watt's engine, Savery and Newcomen, came from the copper mining region. According to Paul Mantoux,

> [Savery] was familiar with the ever-growing difficulties of working copper mines, where, after a certain depth had been reached, it became almost impossible to get rid of the water which flooded the galleries; the pumps which had to be used one above the other were expensive to set up and did not answer very well. It was in order to replace them that Savery invented his engine. […Newcomen] no doubt heard of Savery, whose experiments had taken place not far off [in Devonshire]. (Mantoux [1928] 1961:313, 315).

Other groundbreaking technical innovations in this period took place in the industry. One was the utilization of the reverberatory furnace since the 1680s, with which copper could be smelted using the heat of coal without direct contact, so that the material would not be contaminated with impurities. It seems the technology was adopted from lead smelters, and then used for the first time at industrial scale to smelt copper. Only later would it be adopted for the production of pig iron (Burt 1995). In 1697 rolling mills were already operating to flatten copper and brass ingots—

eighty years before rolling mills were used in the iron puddling process (Hamilton [1926] 1967, 332-49).

The combination of high growth rate of copper output, high exports, and technical innovations indicate that the role of copper in the Atlantic economy immediately before or even in the beginning of the Industrial Revolution has been underestimated. It could even be said that cotton "took off" reaping the results of a previous copper boom, as will become clear in the next subsections.

Copper in the Seas: War and Transportation

Slave trafficking and the Caribbean sugar colonies trade intensified sea faring. When sailing warm waters towards Africa and the Caribbean, the hulls of ships became infested by shipworms and seaweeds, requiring increased maintenance and higher costs, or resulting in slower ships. Wars fueled concerted efforts to solve this problem, and a first attempt to use copper sheathing to protect the wooden hull was the *Alarm* in 1761, during the Seven Years War. But it was the Anglo-French War of 1778-1783 that saw the systematic sheathing of the Royal Navy. Copper sheathing proved to be militarily important in two respects: it not only decreased maintenance time and costs, but also increased the speeds of the vessels, which could be decisive in combat.

From the beginning, however, there was a technical problem to be solved. Copper was then too fragile to be used in bolts, and so iron bolts were used. But the contact between copper plates and iron bolts in salty sea water causes electrolytic corrosion. However, the urgency of the war precipitated the adoption of copper sheathing with iron bolts. In 1778 a large number of small ships was sheathed. Subsequently, there were orders to sheath all ships below 32 guns, and then all ships below 44 guns, and then, in February 1779, the battleships *Invincible* and *Russell* (74 guns each). From then on, the Navy Board ordered in series, working to incrementally improve the problem of corrosion by employing different metal alloys and protective paper. By 1782 the whole fleet was coppered, totaling eighty-two capital ships, fourteen of 50 guns, 115 frigates and 102 sloops and cutters (Harris 1966; Knight 1973; Cock 2001).

In the aftermath of the War, Britain lost its American continental colony, but copper sheathing nevertheless conferred a key tactical advantage (greater speed) over the French ships that helped retain the Caribbean sugar colonies under British rule. The victory in the Battle of the Saintes in 1782, in which the French planned to invade Jamaica, seems decisive (Stevens and Wescott 1920:212). Before the end of the war, however, several shipwrecks occurred, which were traced back to the corrosion problem. Copper sheathings were suspended in 1782. If the galvanic action problem could not be solved, it would have been a severe blow for the copper trade. The problem was ultimately overcome by using rolling mills to produce harder copper bolts. Between 1788 and

1792 the average annual consumption of copper by the Royal Navy was of 358 tons. During the next five years (during the French Revolutionary Wars), this number trebled to 1047 tons (Report from the Committee 1799:175).

Besides military use, copper sheathing was important in merchant shipping, and especially so in slave trafficking. It started slowly around 1775, with a sharp increase in 1799, so that in 1800 already 75% of slave ships were coppered and in 1805 this number approached 90%. Copper sheathing doubled the lifetime of ships and made them on average 16% faster, which meant saving 11 or 12 days to traverse the Middle Passage. It resulted in a reduction of the mortality rate of slaves transported, which for sheathed slave ships was halved. These savings would have been enough to make copper sheathing appear as a good investment for slave dealers (Solar and Ronnback 2015). Copper sheathing was adopted by 3.3% of the merchant ships in 1786 and 17.9% in 1816, with a concentration among warm water routes to the West and East Indies (Rees 1971; Solar 2013).

Sugar and Copper: Cheapening British Labor

The massification of sugar consumption was one the most important processes of the Industrial Revolution. Between the late seventeenth and the end of the eighteenth century it was transformed from "a luxury of kings into the kingly luxury of commoners" (Mintz 1985:96, 148). Sugar was a rarity in 1650, a luxury in 1750 and a virtual necessity in 1850 (Higman 2000). There is no doubt that working-class consumption of sugar is related to the factory system, with its emphasis on saving time and market, monetized relations, and the fact that women and children were put to work, resulting in a decline in domestic bread-making. As cheap, slave-produced source of calories, sugar helped to decrease the cost of subsistence of British workers, and therefore to increase the profits of the British industry. This transition from luxury to mass consumption required an expansion in scale, and in the case of British consumption it roughly coincided with the expansion of the sugar frontier in the British colonies from Jamaica to Guyana. At the level of the world-economy it also entailed the rise of Cuban production (Tomich 2015).

The heart of the process of sugar production from sugar cane is the boiling house run by skilled slaves. After juice was extracted from sugar cane in the mills, it had to be boiled, so that sugar would crystallize. The basic component of the boiling house was a row of copper cauldrons (a battery), set over a furnace, also called "Jamaica." Usually there were five or six cauldrons in a battery. The juice was clarified in the first two cauldrons and crystallized in the remaining. After the final cauldron, the syrup was separated into crystals and molasses, with which rum was made (Galloway 1989:106). These operations required heat exchange in the wet environment of a vessel producing an edible material. Copper's excellent heat conductivity, high melting point and malleability, resistance to corrosion and ease of cleaning, wettability (preventing that adhered bubbles impaired heat conductivity), made it the ideal material for the cauldrons, saving fuel and time in the production of sugar (Tomich 1990:168).

The "Red Gold": Copper for Slaves, Gold and Ivory

The Industrial Revolution transformed Atlantic slavery, expanding it in massive scale to supply the increasing demand for cotton, sugar and coffee (Tomich 2004:56-71). Copper was widely used in exchange for slaves in Sub-Saharan Africa, who were then transported to the plantations in America, and colonial products finally brought back to Britain in a triangular trade (Williams 1944/1994). English trade of copper and brass with Africa rose sharply in the period 1710-1730 (from ~100 to ~900 tons annually). From 1740 to 1800 it trebled again to 3,000 tons. The sum of English customs data from 1699 to 1808 amounts to a total of 17,886 tons, but this is very likely an underestimation (Herbert 1984:145, 181). Thomas Williams, owner of Anglesay's mines and smelting works, petitioned to the Parliament in 1788:

> the petitioner and his partner have laid out a capital of £70,000, and upwards, to establish themselves in the aforesaid manufactories, which are entirely for the African market, and not saleable for any other; and that the petitioner has lately been informed, that a Bill is now depending in the House, for the purpose of regulating, for a limited time, the shipping and carrying slaves, in British vessels, from the coast of Africa, which the petitioner is informed, and believes, will greatly hurt, if not entirely ruin, the British trade to Africa in the Manufactures aforesaid, whereby the petitioner and his partners would lose the greatest part of the aforesaid capital… (cited in Inikori 2002:470)

Williams must have known that the metal trades of Birmingham (including gun-making) were heavily involved with the slave trade (Fryer 1984:417-20). Cargos to Africa included a wide variety of commodities, such as textiles, guns, metals, paper, tobacco, beads, and others. While the European demand for African goods was constant (gold, slaves, and ivory, plus some regionally or seasonally produced items), the African demand was extremely complex, varying culturally, geographically, and in time. Besides, Africans generally demanded an assortment of goods, rather than a single item. This forced European merchants to turn their ships in African entrepots into "floating supermarkets" (Herbert 1984; Williams [1944] 1994).

Some of the copper items demanded by Africans were utilitarian, like copper kettles and pans. Copper was used as means of exchange in the form of ingots, rods and *manillas*. However, in African societies copper was embedded in a non-capitalist system of beliefs and meanings (hence the terms of exchange often being considered irrational by Europeans). Mostly, copper was used for non-utilitarian purposes, as means of artistic expression and symbol of status. According to Eugenia Herbert, copper had for the Africans a social meaning similar to that of gold for Europeans, a "red gold" that represented beauty, status, and power. It was an important component in myths and legends and was used in rites of passage. No doubt that it was an essential item in the purchase of African goods. However, African buyers carefully checked the quality of copper by evaluating its material properties of redness, luminosity, and sound, which served to embed it into ritual and mythological systems. Rejection of items was not uncommon, and the reasons for rejection (or acceptance) were not clearly understood by European merchants (Herbert 1984:123-5).[5]

Drunkenness and Copper

The drinking habits of the British working class during the Industrial Revolution were witnessed by Friedrich Engels:

> That they drink heavily is to be expected. Sheriff Alison asserts that in Glasgow some thirty thousand working-men get drunk every Saturday night, and the estimate is certainly not exaggerated; and that in that city in 1830, one house in twelve, and in 1840, one house in ten, was a public-house; that in Scotland, in 1823, excise was paid upon 2,300,000 gallons; in 1837, upon 6,620,000 gallons; in England, in 1823, upon 1,976,000 gallons, and in 1837, upon 7,875,000 gallons of spirits. (…) On Saturday evenings, especially when wages are paid and work stops somewhat earlier than usual, when the whole working-class pours from its own poor quarters into the main thoroughfares, intemperance may be seen in all its brutality. I have rarely come out of Manchester on such an evening without meeting numbers of people staggering and seeing others lying in the gutter. (Engels [1845] 2009:137)

[5] On copper in the slave trade, see also Inikori (2002:467-472) and Harris (1964:9-10).

Collective drinking involved rituals that have their roots in the *potlach*, like offering rounds of drinks as mutual obligation within a group. Capitalist modernity appropriated and transformed these old customs during the Industrial Revolution in Britain, for example by introducing the counter to sharply separate seller and buyer. The intensified drunkenness described by Engels also depicts an intensified function of escapism, of evasion from (or active resistance against) the daily brutality of exploitation. During the Industrial Revolution, just as exploitation and alienation were intensified, beer making was upscaled. For the brewers, to take advantage of the larger market, the scale of the manufacture had to be increased. This was done most economically by increasing the size of utensils to achieve economies of scale, as "the number of workers did not increase proportionately to the size and capacity of vat, copper, or 'back.'" Between 1738 and 1830, beer production in Britain increased from 915,000 to 1,441,000 barrels; among the 12 biggest breweries, it came from 383,000 to 1,200,000 (or from 42 to 85% of the British market). This new centralized, enlarged capacity required new coppers. Gin production also soared: from half a million gallons in 1684 to 5 million in 1737, and again to 11 million around 1750 (Mathias 1979:216, 220; Schievelbusch 1992:153).

But the intensification of drunkenness was reflected in the beverage itself, with the rise of liquors and spirits (gin), both more industrialized (distilled) and with a higher alcohol content, therefore leading to an intensified and faster drunkenness (Schievelbusch 1992:147-67). Thousands of miles away from Britain, in the Caribbean, slaves drank rum, derived from sugar cane. Again, they were keeping their African customs, where palm wine served spiritual functions among the Igbo and Akan, at the same time that were transforming them to cope with their new situation (Smith 2004).

Besides brutal exploitation and drunkenness, another element was common at the background of rum, gin and beer: again, copper. Beer-, gin- and rum-making require boiling operations. Boiling is carried out in copper vats, because copper has good heat conductivity and good wettability (i. e., the bubbles easily flow away from the surface, instead of forming a insulating layer) (Lewis and Young 2002:271-2). Both properties ensure the energetic efficiency of boiling operations, and therefore beer, rum, and gin can be cheaper.

Copper, Cornwall and the Steam Engine

The great innovation of Watt's steam engine that made it superior to the previous models from which it developed was the external condenser. This was a macroinvention, which followed by a long series of microinventions "set in train long trajectories of advance that resulted in great increases in productivity." (Allen 2009:ch. 6). Efficiency was especially important for the working of Watt's engines in the copper mines in Cornwall, as the payment of royalties amounted to a fraction of efficiency gains (a third of the amount of the coal saved) (Rowe 1953:79). Contrary to coal mines, where fuel was practically free of cost, in copper mines the cost of fuel could hinder the operation of the engine (Farey 1827:169). This drive was intensified by competition with local engineers who built alternative engines (Trevithick's high-pressure engines, Hornblower's compound engines) without charging royalties. On top of that the discovery of the surface mines in Anglesay (Wales) put great pressure on the price of copper and therefore on Boulton and Watt's profits coming from Cornwall. Here comes to the fore the importance of the field engineer, who daily worked on the engines to improve their efficiency and reliability. Boulton and Watt's main engineer in Cornwall was William Murdock:

> In developing its powers [of Watt's steam engine], and extending its uses, the great merits of William Murdock can never be forgotten. Watt stands first in its history, as the inventor; Boulton second, as its promoter and supporter; and Murdock third, as its developer and improver… And at length William Murdock, after he had acquired sufficient knowledge of the business, was able to undertake the principal management of the engines in Cornwall. We find that in 1779, when he was only twenty-five years old, he was placed in this important position. When he went into Cornwall, he gave himself no rest until he had conquered the defects of the engines, and put them into thorough working order. (Smiles 1890:66, 69)

Murdock worked in Cornwall until 1798, improving the engines for 19 years. Undoubtedly these years were instrumental in making Watt's engines reliable and efficient, and the textile industry reaped the benefits from the 1830s, when they started to be extensively used in the textile mills, allowing urbanization and exploitation of cheap labor (Malm 2016). Besides, Trevithick's high pressure engine, also developed in the copper mines of Cornwall, was later applied in locomotives and steamboats.

In addition to the historical roots of the steam engine, copper as a material is important for its efficiency. This is not surprising, as the steam engine works essentially with controlled heat exchange, and the excellent heat conductivity of copper makes it especially fit for such kind of equipment. Watt preferred his boilers, the heart of the engine, to be made out of copper, as it has much better heat conductivity than iron. Copper is also more resistant to corrosion, an important feature when the material is constantly exposed to water. His key innovation, the condenser, was also made out of copper to optimize heat exchange with the water in which it was submerged. Copper (or brass) was also used in diverse components such as tubes and valves (Hills 1989:76, 124; Farey 1827:394, 309-383, 322). Boulton and Watt became investors in the copper mines, in part to secure the payment of royalties, but also with an eye to the provision of an essential material for their equipment (Tann 1995).

Monetizing the Market Economy

The Industrial Revolution produced remarkable changes in the mode of exchange of necessities of life in Britain. With proletarianization and urbanization, many products that were previously homemade—like jam, butter, bread, beer, cheese, clothing, and vegetables—now had to be procured in the market. The same for the sugar imported from the Caribbean that provided essential complementary calories. The truck system in distant mines and work colonies were in the same situation. What was necessary was retail money, fitted for the cheap commodity, instead of the large, more valuable coin made out of silver or gold. These retail tokens were made out of copper. Between 1775 and 1821 it was actually left to private entrepreneurs to issue their own token, as the Royal Mint did not consider it its task to provide coins in such base metal, but only in gold and silver (Mathias 1979:ch. 10).

The biggest issue of private copper tokens was promoted by Thomas Williams, the entrepreneur who owned the copper mines of Anglesay, as well as smelting works. Of course, this was convenient to him, as the owner of the mines, but the initiative was imitated by ironworks entrepreneurs (Mathias 1979:ch. 10). As put by Marx, "copper coins replace gold in those regions of the circulation of commodities where coins pass from hand to hand most rapidly, and are therefore worn out most quickly. This happens where sales and purchases on a very small scale recur unceasingly" (Marx [1867] 1990:223). Interestingly, tokens issued by Matthew Bolton started to accumulate in London breweries, as the cheap beer produced in copper boilers was bought with copper tokens. Copper tokens were also used to boost nationalism in a time of wars, with special issues to commemorate victories in military battles (Mathias 1979:ch. 10).

Sorting Out and Extracting Copper

One should not forget that the formation of a mineral vein is an improbable process in a universe dictated by the law of entropy, tending towards a "uniform soup." The existence of a mine, meaning a region of the crust of the Earth in which a particular material appears "sorted out," in unusually high concentration, implies a previous energy expenditure, a process by which the material was concentrated. In Cornwall the copper veins formed around 250 million years ago, from alterations in the base granite formed circa 200 million years earlier from volcanic activity. It happens that this granite had relatively high concentrations of uranium, whose radiative decay generated considerable heat. This situation promoted a hydrothermal deposition: the circulation of heated fluids within the granite mineralized copper and other metals. Those fluids flowed toward veins, and when they cooled down again, the crystallization temperature of the metal was reached, forming the ore deposits with circa 6% of copper that would be extracted by the miners 250 million years later (Selwood et al. 1998). The concentration of copper in the the lithosfere is about 100 parts per million or 0.01%, meaning that the geophysical process just briefly outlined concentrated about one million tons of metallic copper by 600 times (Selwood et al. 1998:224). The fact that mineral vein formation and ore extraction and processing were asynchronous, separated by hundreds of millions of years, should not obfuscate the understanding of their continuity, and that most of the energy necessary for the sorting of copper out of a "uniform soup" was spent before any human intervention. The copper mines are then a commodity frontier, a place where the "creativity of nature" is appropriated and commodified free of cost for capital (Moore 2000; Prigogine 1996).

In 1787, there were 7 thousand persons employed in the Cornish copper mines (Jenkin [1927] 1972:91). By this time, gunpowder and the steam engine (for drainage) were already in use. About sixty Newcomen engines were working in 1778, but the cost of coal was high. In this same year the first Watt engine was installed, opening a new era, and by 1798 there were forty-five of them (Tann 1995; Jenkin [1927] 1972:100-1). Labor conditions were very harsh, in spite of technical improvements. Miners were subject to heat, moist, sulfur vapors, dirt and the danger of death in a waterlogged mine. Nevertheless, witnesses report with great surprise that the miners used to sing while working. They worked under contract or tribute. A great mine conditioned the lives of hundreds of men, women and children living in the neighborhood. Children of both sexes as young as eight years of age were apprentices in jobs at the surface. There were no schools. At twelve or fourteen the boys started to work underground with their fathers to learn the skills of the Cornish miner. As the girls grew older, they continued working as "bal maidens," breaking the copper ores, usually until getting married (Jenkin [1927] 1972:ch. III-IV). Next, the ore should be sifted and washed free of earth, sand and loose materials. Afterwards it was calcined to release sulfur and arsenic, and next it was drenched with water, releasing more arsenic and sulfur. Since there was no coal deposit in Cornwall, smelting was concentrated in South Wales. Thereby, the same ship could carry copper ore from Cornwall to Swansey for smelting and return with coal for use in the Cornish steam engines (Rees 2000:3-23; Jenkin [1927] 1972:114-5).

William Pryce, a local geologist who surveyed the area in the eighteenth century, complained about the installation of copper smelters on the other side of the Swansea Channel (South Wales), with "their vast opulence" and "whose interest it must be to support the present system, the channel of their wealth"; he lamented "the exportation of their raw staple, in order to give other countries the benefit of its manufacture," which seems to characterize Cornwall as a peripheral region within a core state (Pryce 1778:278-279). The final quarter of the eighteenth century, when the Anglesay mines flourished, caused great suffering for Cornish miners, as the Anglesay's cheaper superficial copper provoked falls in price that led to the closing of many Cornish copper mines (Jenkin [1927] 1972:156-66).

Industrial Innovations

The copper and brass industry pioneered some industrial innovations that would later be applied in ironworks. The already mentioned reverberatory furnace was applied industrially by the copper trade since the 1680s. Two important innovations improved the production of plates and wire from copper ingots. Plates had previously been produced through "battery," or the use of hammers to reduce the thickness of ingots and then give them form. By the end of the seventeenth century rolling mills replaced battery mills, but battery continued to be used for hammering round plates of metal into pots, pans, and similar articles until the end of the eighteenth century. Wire drawing in Elizabethan times was done with a very raw method: men sat in swings opposite to each other with a thin plate of brass attached to a girdle fastened around their waists, stretching forth their feet against a stump they shot their bodies from, until it was stretched into a wire. By 1697 plates of brass about 70 pounds were cut into 7 or 8 strips, and these strips were stretched on the rolling mill to the set thickness. The strips were then cut into many long threads, and were drawn through holes in iron of the required size. By 1700, casting, a process actually rather old, started to replace battery for small metal articles.

Around 1770 the process of stamping was developed, with the impulse of the use of rolling mills. It consisted of a machine with a moving weight or hammer, faced with soft metal, which was to move between the rods. The hammer was allowed to fall on the sheet metal, which was laid on a striking block over a fixed die or relief model of the desired pattern, and thereby the pattern would be forced into the sheet metal, forming the impression. When applied to the manufacture of copper buttons for textiles it caused high efficiency gains, since before that the patterns had to be engraved by hand (Hamilton [1926] 1967:332-49). Rolling mills were also used to solve the corrosion resulting from the use of iron bolts in copper sheathing. Copper bolts with sufficient hardness were produced in 1783 by Thomas Williams' firm (Harris 1964:45-50). The application of rolling mills as early as the 1690s indicates that copper and brass mills were pioneers in setting up continuous industrial processes, a key feature of the modern large-scale factory system in which the pace of production is dictated by the machinery. Again, the copper industry anticipated the iron industry, which would use rolling mills only in the 1780s in Cort's puddling process.

Another process that came into use by the end of the eighteenth century was "plating," with particular importance for the button, buckle, and toy trades, by which silver could be plated over copper in the manufacture of buttons, snuff boxes, and other small items, so that copper looked like silver (Hamilton [1926] 1967:348). Interestingly, the obverse operation was tried later for the African market: cast-iron *manillas* electroplated with copper. Contrary to the European attitude, not only the Africans thoroughly rejected the imitation material, but Birmingham traders lost market share because of this unscrupulous trader (Herbert 1984:202).

The metal works, where ingots and plates produced mainly in South Wales were worked into final products such as pans, kettles for sugar refining and beer-making, guns and *manillas* for the African trade, were concentrated initially in Bristol and later in Birmingham, but also in Sheffield. Here, as well as in many small items produced in small-scale firms, the hand of the skilled worker was central. This tendency to produce small items likely derives from the difficulties of transportation in Birmingham (Berg 1994:264-69; Hamilton [1926] 1967:122-39). In the emerging engineering sector, the millwrights certainly considered copper, with its unique set of properties, as part of their basic technical repertoire (Berg 1994:258-61).

Copper and Textiles

In 1792, 60% of all white cotton cloth produced in Britain was sent to the printers. Calico printing in Britain and Europe in general was the result of the enormous impact of Eastern design, technique, and manufacturing on European fashion. The introduction of Indian cottons created a fever that lasted for a century, coinciding with the emergence of nearly uniform European consumer taste and fueling the development of a world market. Calicos became the most important commodity for the great European trading families (Chapman and Chassagne 1981:4-5). British protectionism (to save the wool and linen trade) resulted in the prohibition of wearing Indian calico prints (1701) and of wearing British printed cottons (1721). The calico acts slowed the growth of the industry, but the law could be evaded by printing linen or cotton-linen mixture (fustian), besides export and migration to France. The ban was lifted in 1774. In the 1760s calico printing was concentrated around London, but in the 1780s Lancashire was already dominant in the trade (Chapman and Chassagne 1981:8; Tozer and Levitt 1983:21-42).

Here the role of copper was decisive for the printing technique. A more traditional method was the one using copper blocks. However, productivity increases in spinning and weaving and finishing generated a bottleneck in the printing trade. From the 1760s the copper plate printing machine started to be used. The machine was manually operated, pressing the cloth on a flat engraved copper plate and spreading the color for the next repeat. The greatest technical achievement, though, was Thomas Bell's roller printing (1785). It consisted of an engraved copper cylinder, powered by a waterwheel or steam engine that could operate continuously. By 1793, the Indians—who previously dominated the trade and were imitated by the British—had to employ 15 operatives for each one employed in a British factory. In 1808, one man and a boy could deliver eight calico pieces in a day with the block printer, 12 pieces with a calico press printer and 200 pieces with the cylinder printer (Chapman and Chassagne 1981:21, 44; Tozer and Levitt 1983:21-42; Parkes 1830:554-5; Cunha 2019).

The reason why the cylinder was made out of copper becomes clear when one focuses on the process of engraving. The principle is that a small steel cylinder is engraved by hand once, and roller pressure against a larger copper cylinder is used to replicate the pattern several times *in intaglio*. Copper was used because it was a softer metal that could be engraved if applied pressure against a harder engraved metal. Were it not for this, the pattern would have to be engraved by hand many times in a much larger cylinder, and there would be much less productivity improvement. The importance of roller printing was well described by the contemporary historian Edward Baines: "cylinder printing […] bears nearly the same relation in point of dispatch to block printing by hand, as throstle or mule spinning bears to spinning by the one-thread wheel" (Baines 1835:265, 267-8; Encyclopedia Britannica 1911:698).

After printing, textiles were also treated with steam in the "steamer," again in copper cylinders, to improve the colors just printed. Here, iron could not be used because it would have spoiled the colors. Copper was also used in lye baths in copper cauldrons, cleansing in copper vessels, copper cylinders heated by steam (calendaring) during finishing operations and as a mordant to fix colors in printing (Parkes 1830:556-9, 390-1, 403, 554, 569; Baines 1835:252).

Transport and Communication

The copper mines not only provided copper that was transported worldwide, but it is also part of the history of transport and communication, beyond the already discussed copper sheathing of vessels. The high-pressure steam engines developed in Cornish mines by Trevithick were soon to be used in locomotives and steamboats, and copper wires were the essential component of telegraphy. The high-pressure engine was used for the first time in a locomotive in the ironworks of Coalbrookdale in 1802, and steamboats using Trevithick's engines were extensively used in the Mississippi carrying cotton from the plantations in the nineteenth century. The use of high-pressure engines in transportation is favored by the fact that it has a higher power to weight ratio (Johnson 2013:93-4).

In the 1830s, the telegraph started to be used in the logistics of the London railways (Liffen 2010; Barton 2010). Again, the material properties of copper stood out. As put by C. A. Steinheil, the German developer who set the standard for material selection,

> the *conductibility* of metals differs… copper, for example, conducts six times better than iron. The metal most suitable… that which can best

> subserve the purposes in this technical application… are copper and iron wires. But though iron is six times as cheap as copper it must be six times the *weight* to have the same conduction power… thus the expense is the same. The iron is the stronger and heaviest (but) the preference is given to copper wire as this metal is less liable to *oxidation.* (cited in Blake-Coleman 1992:144; emphases mine)

The Electric Telegraph Company bought the telegraph patent in 1847, soon after the "railway mania" stock market bubble of 1844-47, which fostered the search for fast and reliable information among investors. The telegraph soon started to be used to transmit business information in real time, connecting the Royal Exchanges of Manchester, Liverpool, and London, the world centers of commodity exchange at the time (Barton 2010). The *Manchester Courier* thus reported on the new service:

> We have had the pleasure of inspecting and seeing at work the electric telegraph at the office of this company… The telegraph company are in possession of a complete set of signals for shipping arrivals, cotton markets, share markets, and in fact everything which can be supposed to be needed in a large commercial town like this. (cited in Barton 2010)[6]

Zooming Out: The Role of Copper, World-System Dynamics, and Method

Now we can perform the thought experiment or "historical possibilitism" discussed above. What would be the consequences if we removed copper from the picture? The consequences would be so numerous that we can classify them for analytical purposes: the ones due to copper's material properties, the ones due to copper's historical contingencies, and the ones related to the cultural meanings of copper. The consequences deriving from the material properties of copper are related to its use-value and how it is used in different production processes and products. The ones deriving from the historical contingencies refer to those technologies, processes, and events that, having been developed or having taken place in one part or process of the world-economy, were later used, or had consequences, in other parts or processes of the world-economy. Finally, the ones derived from the cultural meanings of copper are related to the "external arena" (exchange of

[6] For an analysis of the importance of copper from 1830 to 1870 that includes the internationalization of ores smelted in Swansea, see Evans and Saunders (2015).

luxuries between different systems), historically-specific cultural traits, and tendentially anti-systemic processes.

In the first category one can compute the increased cost of sugar, as boiling operations would be less efficient, entailing additional energy expenditure. This increased cost of sugar would have caused an increase in the reproduction cost (wages) of the British labor-force. Due to the same issue of energy efficiency, beer would have become more expensive. Another outcome would have been a significant decrease in the efficiency of calico printing, without the malleability of copper that allows machine-engraving with a steel cylinder. Without copper sheathing, an increased mortality and consequent increased price of the slaves transported to the American South and the Caribbean would have followed, and this, in its turn, would have made American cotton and British sugar more expensive. Again, this would have reflected in the cost of British labor. Regarding transportation, there would have been an increase in the cost of exports of commodities in general. Without copper, heat exchanges in the steam engine would have been less efficient, and consequently fossil mechanical energy would have become more costly. As a consequence, energy efficiency in industrial processes in general would have decreased, leading to increased costs for the production of commodities in general. The absence of cheap metal coins would have caused difficulties for retail transactions of cheap commodities. Finally, a less efficient telegraph would have resulted in increased costs for business communication.

In the second category (historical contingencies) consider: the removal of copper would have hindered the "primitive accumulation" and early Industrial Revolution (1700-1800) in which a "copper boom" in the Atlantic economy prepared the terrain for the "take off" of cotton. This was achieved by facilitating slave trafficking and consequently the provision of an initial stock of slave labor in the sugar and cotton plantations (copper sheathing), by facilitating sugar refining itself as the material of boilers, and by the technical achievements in mining and industrial processes that would later be diffused to the ironworks (reverberatory furnace, rolling mills) and the cotton industry itself (the steam engine). In the absence of copper, the development and efficiency gains of steam engines would have been delayed, making fossil mechanical energy more expensive for all the sectors that used it later (cotton mills from the 1830s), and delaying the development of faster means of transportation (the locomotive, steamboats). Were it not for copper sheathing, wars against France would have been longer and could possibly result in defeat and loss of all or part of the sugar-producing Caribbean islands. Without the industrial development in the copper trades, the development of rolling mills in the metal trades would have been delayed, affecting iron mills that applied it later, which in its turn would affect machine-building and engineering as a whole.

In the third category (cultural meanings): had the West African elites not valued copper as a "red gold," slaves would have been more costly, reflecting in the prices of slave-produced commodities cotton and sugar, and again in the cost of British labor with more costly sugar and clothing. The obverse is that were it not for the despise of Europeans for copper, the development of plating methods could have been delayed. Copper also enabled the cultural meanings of drinking for both British workers and African slaves to be potentialized, and without it the drinking market would not have expanded to the same scale. The shrinking of this important "escapist" strategy of the laboring might have resulted in more explosive, rebellious class antagonism, even though the act of drinking to avoid labor can also be seen as an act of resistance in itself.

Copper and World-System Dynamics, 1700-1840

The above analysis illustrates the centrality of copper to the larger dynamics of the world-economy, which can now be elaborated and put into perspective with previous studies by Blackburn (1997) on the "Atlantic boom", Wallerstein (2011) on the dispute for hegemony over the world-economy between Britain and France, Saunders and Evans (2015) on the importance of copper in the Atlantic economy, Zahedieh (2013) on colonial markets and British industrialization, and Bunker and Ciccantel (2005) on the dynamic relation between industrial and transportation innovations in the "race for resources" in the world-economy.

This study highlights a previously overlooked dynamics of the world-system before and during the Industrial Revolution, namely a copper boom that preceded the cotton takeoff, from roughly 1700 to 1800. This complements the suggestion of Blackburn (1997:ch. 12) that the "Atlantic boom" was instrumental for British industrialization, even though he overlooked the key role of copper. The copper boom can be seen in the development of the Jamaica Train for sugar production in the Caribbean, copper boilers for the production of beverages in the colonies and in Britain, the slave trade using the "red gold," the transport of slaves with reduced mortality, the industrial technologies of reverberatory furnace and rolling mills already by the end of the seventeenth century (only later used in ironworks), the steam engine developed in copper mines. All of them depended on copper, culminating in the development of copper printing of textiles and copper sheathing with the aid of the associated innovation of copper bolts. This "takeoff" is confirmed by the high rate of growth of the copper sector in the period. Therefore, when Blackburn (1997) claims that "the plantation revolution preceded industrialization by at least a century" (515), he is overlooking that the extraction and smelting of copper and the manufacturing and transportation of copper goods were already simultaneously promoting innovative industrialization in Britain, as already noted by Zahedieh (2013). Also Wallerstein overlooks the role of copper even while recognizing that the main difference between Britain and France in the struggle for hegemony was the Atlantic trade (2011:101). The high growth rate of the British copper sector coincides with the period that Wallerstein identifies as the Franco-British dispute for hegemony (1689-1763) (Wallerstein 2011:ch. 6; Crafts 1985:23). The development of the copper trades was a key factor that eventually led Britain to win the contest as the results of the "copper boom" were absorbed and expanded by the takeoff of cotton. This conclusion gives substance to the suggestion of Saunders and Evans (2015) that copper was important in the Atlantic economy from the 1690s and included industrial, supply-side innovations. However, these authors had difficulties to explain it, because they identified the "modern, industrial consumption of copper" as starting only in the final third of the nineteenth century—but this is not the case of earlier industrial uses of copper including copper printing, the application in the steam engine, or the development of copper bolts. Zahedieh (2013) already noticed that colonial demand impelled industrial innovations in smelting and mining in Britain.

Interestingly, this "copper boom" supports the theoretical analysis of Bunker and Ciccantell on "economies of scale and diseconomies of space" that mediate industrial developments, transport technologies, and trade dominance, generating "positive feedbacks" (2005:84-86). It must be noted that copper sheathing was developed by the end of the period, confirming the pattern proposed by Bunker and Ciccantell according to which economies of scale generate diseconomies of space following the "race for resources" over immense areas of the world-economy, and thus force innovations in transportation. But at the empirical level, Bunker and Ciccantell, just as Blackburn and Wallerstein, bypassed the "copper boom," by transitioning directly from "wood to steel", eliding copper sheathing (2005:ch. 5). This empirical gap in their account weakens their proposition that Britain was overdependent on a military navy because its commercial fleet was less efficient until the development of steel steamships in the second half of the nineteenth century. Copper sheathing also represented a qualitative innovation—protection from tropical warms and decreased friction resulting in greater speeds—deviating from Bunker and Ciccantell's emphasis on increased volumes. Copper-sheathed ships were the most advanced sea transport technology around 1800, encompassed advantages in both commercial transport in tropical waters (especially the slave trade) and war, and in the general context already presented copper can be said to constitute a "generative sector" that preceded the steam and steamship boom described by them.

Yet, the very notion of "leading" or "generative" sector should be considered with a grain of salt. What the application of the figure-ground method shows is that even when copper was arguably replaced by cotton as the "generative sector" (see Table 1), its use-value was still indispensable for the accumulation of capital, as exemplified by its use in the process of textile printing, but also by the permanence of all other applications of copper even after cotton "took off." In other words, instead of the concept of "leading" or "generative" sector, the notion of a constellation of commodities woven by value relations (meaning, encompassing the contradiction between use-value and exchange-value) seems more adequate.[7] The concept of "ecological regime" encompasses these considerations, as it is based on value, and the related circulating capital, instead of the a-historical notion of "matter" or the Schumpeterian "factors of production."

The Copper Case: A Reflection on Method

This study makes possible a reflection on the method itself. Most fundamentally, without the figure-ground movement used to study the dynamics of the world-economy and how it is related to processes involving copper, those processes would remain reified, unrelated. The figure-ground movement made possible the reconstruction of the world-systemic dynamic by relating it to those partial processes, and the reconstruction of the partial processes as moments of the development of the whole. Contrary to other commodities, like cotton, the essential relevance of copper for the Industrial Revolution cannot be grasped without a relational method.

This exercise also highlights the importance of including use-value, culture, and historical contingency when using the figure-ground method. This implies that simply analyzing a "commodity chain," if this is understood as the analysis of abstract aggregate variables ("value added," volumes of production or trade, etc.), is insufficient. It is necessary to enter the "hidden abode of production" to inspect how the unique qualitative properties of a material are applied in order to valorize value, as in the case of the use of copper in the printing of textiles. It is necessary to take into consideration cultural mediations that reinforce or mediate the production or trade of certain commodities, as in the case of the "red gold" used in the slave and gold trade—which conforms the assertion of Wallerstein (1974) that exchanges with the "external arena" (between two systems) assume the form of an exchange of luxuries. And it is necessary to take into consideration historical contingencies, in which the development of technologies and events taking place in certain parts and processes of the world-economy might have unintended but important consequences in other parts and processes, as the steam engines developed and perfected in Cornwall that were later applied for the transportation of cotton in the Mississippi and in cotton mills in Lancashire. Finally, it is important to add to the "units or acting agencies" nature itself. In this case it entailed the very formation of copper veins in a natural nuclear reactor, which were subsequently transformed with the conversion to a commodity frontier (from mineral vein to mine, under a historically-specific set of conditions). Therewith we actively engage in an effort to break the real abstractions of nature and society as two discrete realms of reality (Moore 2015). Regarding the notion of ecological regime, this study suggests that not only the conditions of possibility of "flows of cheap energy, food, raw material, and labor-power to the organizing centers

[7] For a similar argument regarding the importance of Sicilian sulfur for the Industrial Revolution, see Cunha (2019).

of world accumulation" should be included, but also the processing of these flows in the "hidden abodes of production" within those centers (Moore 2015:158).

This study also provides a historical case of the pattern that Wallerstein called "multiple layers of coreness and peripherality" of the world-economy, as Cornwall presented all the characteristics of a peripheral area within a core state. Wallerstein used the expression while admitting that his formulation of core and periphery was perhaps insufficient to capture these patterns (Wallerstein 1982:91-92); using Hopkins's figure-ground method to trace the relations between the parts of the world-economy, instead of considering "core" and "periphery" as reified "ideal-types" coinciding with the borders of national states, this peripheral condition of Cornwall within a core state came to the fore: an extractive region providing raw materials for industrial processing in other regions within Britain (South Wales, Birmingham).

Finally, in spite of using what Milo (1990) calls "historical possibilitism" as a method of experimental history, the use here differs from the one of Fogel (1965) on the American railroads in important aspects. Here copper—generally neglected as essential for the Industrial Revolution—is shown to be essential based on its use value, cultural valuations, and historical contingencies. In Fogel, railroads, generally considered essential for American growth, are experimentally removed from the American landscape, and, with the use of econometric models, they are shown not to be essential. Fogel claims that every use of the railroad could have been substituted, without significant impact on the American "economic growth." The problem here is that it is assumed that capital accumulation is the only and absolute driver of history, devoid of contradictions, and substitution in abstract terms does not impact history. This econometric approach is ultimately a-historical, as it blurs the contradiction between use value and exchange value and its historical specificity, and history thus becomes an "economic history" in which commodified relations and the predominance of exchange value are taken for granted, abstracting from culture, materiality, and historical contingencies. In fact, this contradiction appears surreptitiously in Fogel when he says that there were "many possible growth paths" that could have happened without the railroad (Fogel 1967:237). But is this not, then, a different history altogether? Fogel's assumption of absolute substitutability implies that history would be ultimately reversible. But as put by Sewell (2008), "mathematical economics… reproduces the abstraction of universal exchange as if it were the whole truth about the economy, rather than one dialectical pole in a fundamentally contradictory process." This study on copper does not necessarily claim that copper was unsubstitutable for all of its uses, but it does claim that removing copper from the picture would produce a major impact on the historical development of the world-system.

Conclusion

I have argued that copper was an essential material for the ecological regime prevalent during British hegemony, starting around 1750 (the Industrial Revolution), and that this is, at the same time, a demonstration of the effective existence of an ecological *regime* as a complex constellation of relations woven by a global structuring category, value. The study also revealed an overlooked dynamic of the capitalist world-economy immediately before and during the beginning of the Industrial Revolution (~1700-1800) in which copper played a key role: a "copper boom" in the Atlantic economy, which, it was argued, was instrumental for the British in taking the lead against France in the struggle for the hegemony over the world-economy. Finally, this piece can also be considered an example of the use of the "figure-ground" method for the study of the world-economy. As a whole, the evidence presented point to a more complex history of the Industrial Revolution, one that is not taking place only in Lancashire and is not only based on the industrial processing of cotton, coal, and iron. The analysis undertaken highlights the intrinsically fetishistic character of approaches that rely exclusively on abstract or "aggregate" variables, ignoring use-value, history, and culture, and therefore challenges the notion of "leading sector".

"Copper – you'll never be gold," and these historical, cultural, and material specificities have world-historical relevance.

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