The Multiple Signatures of Carbon

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Nebenprodukte aus der Entgasung der Steinkohle.

THE MULTIPLE SIGNATURES OF CARBON [1]

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Carbon is the fourth most abundant element by mass in the universe after hydrogen, helium and oxygen. The chemistry of carbon is both ancient and ubiquitous, with applications ranging from fine jewellery to heating, textiles, pharmaceuticals, energy and electronics. How can we present this familiar stuff, which has played a central role in the history of chemistry, as an exemplar technoscientific object? Wouldn't it be more adequately described as a typical scientific object?

To be sure, carbon is an object of 'pure research'. It emerged in the nineteenth-century as a chemical *substance*, as an abstract albeit material substrate underlying a range of simple and compound bodies. However, this ontological perspective shows only one face of carbon. While scientific research was focused on what is conserved through change, the researchers' attention shifted to what might be changed: Carbon came back as a menagerie of allotropes – fullerenes, nanotubes, graphene and many more – which populate the 'nanoworld', making it a rich source of technological possibilities. The ontological status of carbon in a scientific perspective answers the question 'what is it?' while in a technoscientific approach, the question answered is rather 'what might be performed with it?' or, more precisely, 'what might it afford?' We could thus portray carbon as a Janus and contrast its scientific and technoscientific identities.[2]

However, this contrast provides a far too purified image of carbon. Carbon has assumed so many guises over the course of the centuries that it almost seems to play various *personae* moving with a momentum of their own, inspiring new adventures while exhibiting surprising physical and chemical properties. Diamond, charcoal, graphite, carbon compounds, mephitic air and CO_2 are among the characters that have played – and continue to play – significant roles in science and mythology, in industry and economy alike. Carbon is too ubiquitous, too polymorphic and too important in our

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Front picture: The 'coal tree'. By-products obtained from bituminous coal degasification. Courtesy of the Pharmazie-Historisches Museum, University of Basel.

[2] As we did in the programmatic paper of the GOTO project: B. Bensaude-Vincent, S. Loeve, S., A. Nordmann, & A. Schwarz, 'Matters of interest: the objects of research in science and technoscience', *Journal for general philosophy of science*, 42:2 (2011), pp. 365–383.

history for being reduced to these Janus faces. Such a portrait would overlook the multiplicity of the *modes of existence* of carbon and their various inscriptions in daily life.

Multiple Modes of Existence

As the term 'allotropy' suggests (*allos*: other + *tropos*: manner, way or mode),[3] carbon displays a multiplicity of modes of existence. This chapter explores their coming into being in relation with human history. It tells many stories, ranging from legends about mephitic air and the key role of carbon in building the periodic table to the story of the carbon skeleton as a backbone of life and pillar of chemical industry.

Due to its disposition for creating strong bonds with itself and other atoms, carbon affords robust and stable structures and a host of potential combinations, found both in nature and in human industry. At the nanometre scale, carbon writes a kind of fairy tale. As its bulk molecular structure shrinks to pure surface, it displays a wide range of novel properties and performs a variety of mechanical, electronic, optical and magnetic functions, presented as the promises of enchanted futures.

In stark contrast to these futuristic tales, the story told by carbon deposits looks backwards and is moving inexorably towards a sad ending. Charcoal and oil, the archives of life on Earth, have been excavated and come back into existence as fire and power for human consumption needs. Two centuries after the beginning of the industrial revolution, the vestiges of life accumulated for billions of years in the soil are almost depleted. They have melted into air by a few generations of an ever-increasing population of humans under the form of carbon dioxide. As human societies realized the impacts of their carbon-based technologies, they elected carbon dioxide as a standard and 'mediating machine' to regulate the flow of exchanges between the two *oikoï* or 'world-houses', ecology and economy.

Carbon thus became a buzzword of economic and ecological globalization. Today, any activity correlated with greenhouse gas emissions – that is to say, most human activities – is translated in terms of 'carbon equivalent'. While the notion of 'carbon footprint' epitomizes human impacts on ecosystems, 'carbon equivalence' casts human industry as a natural force exchanging carbon with other lifeforms at a geological scale. Complementing 'carbon accountability', 'carbon trading' has been implemented: Greenhouse gas emissions are priced in carbon equivalent, which brings property titles and credit exchange rules through a series of interconnected carbon markets. Carbon thus becomes a universal unit of currency, an aerial money, a speculative product. "All that is solid melts into air"[4].

Yet the alliance of carbon with market economy is only one of its modes of existence. Instead, we want to consider all of them at once. Carbon is reducible neither to the fashionable abstraction of carbon equivalent, nor to its chemical identity. The simple and unique definition of carbon as an element in the periodic table, like the definition of water as H_2O questioned by Hasok Chang, is obviously too narrow to

[3] Allotropy refers to the ability of an element to form different simple bodies made up of the same atoms bounded together in multiple specific ways.
[4] K. Marx and F. Engels, *Manifesto of the Communist Party* (1848).

contain all its facets and roles in human history.[5] Just as Chang convincingly argues that the formula H_2O does not deserve a monopolistic dominance, we will see that carbon calls for multiple systems of knowledge. Not only is there a plurality of views of carbon in physics, chemistry, biology, materials science and environmental science… but there are many other relevant views of carbon in lay and traditional knowledge. Carbon proves the value of 'epistemic pluralism', and invites for more 'tolerance' among the various forms of knowledge. However, this chapter goes further. It claims that there is no reason to deduce the various facets of carbon from one single fundamental definition. Carbon as a substance, standing beneath all its modes of being, is only but one of these facets. Carbon invites *ontological pluralism* in addition to epistemic pluralism. Although each mode of existence has an 'imperialistic' propensity for configuring the other modes in its own template, all the modes of existence coexist. Kick one of them out by the door, it comes back through the window. In paying attention to the diversity of modes of existence of carbon and their interactions along the line developed by Etienne Souriau and Bruno Latour,[6] this chapter makes the case for an *ontography*: It considers carbon as an agent of 'graphism' in the task of *writing* ontologies.

Carbon Heteronyms

Carbon is polymorphic. Even in its elemental state it takes a variety of allotropic forms, some of them with well-ordered, crystalline structures (graphite, diamond, lonsdaleite),[7] others with amorphous structures (glassy carbon, carbon black, nanofoam), in addition to mixed structures displaying various degrees of order and disorder (charcoal, soot, coke).

Yet some of the allotropes of carbon have quite different physical properties: diamond is hard and translucent, graphite friable, fragile and opaque. Diamond is abrasive, graphite lubricant. Diamond is an electrical insulator and thermal conductor, graphite an electrical conductor and a thermal insulator. Ever since the days of antiquity, diamond has been considered the hardest stone on Earth. Its name, deriving from Greek αδάμας (*a*: 'not' + *daman*: 'to tame') highlights its remarkable property of resistance to all attempts to break it, as well as to the erosion of time: it is an 'everlasting stone', which literally 'cannot be tamed'. Diamond is adamant, refusing to change or to give in. Fittingly enough, it became the symbol of an unbreakable engagement between two persons: 'diamonds are forever'. What on earth could it have in common with the black and brittle substance that leaves a dark mark on a sheet of paper? In contrast to diamond, graphite (derived from the Greek *graphein*: 'to write') is so fragile and soft that it has to be inserted into a hollowed wooden stick to be used. The pencil patented by Nicolas Jacques Conté in 1795 was named 'lead pencil' because graphite was initially considered to be 'plumbagol' or 'black lead', a substitute for the

[5] H. Chang, *Is Water H_20? Evidence, Realism and Pluralism* (Heidelberg, London, New York: Springer, 2012).
[6] E. Souriau, *Les différents modes d'existence*, 1943 (2nd ed. Paris: Presses Universtaires de France, 2009) with a presentation by Bruno Latour and Isabelle Stengers. B. Latour, *Enquête sur les modes d'existence. Une anthropologie des modernes* (Paris: la découverte, 2012). Eng. tr. Cathy Porter, *An Inquiry into Modes of Existence* (Cambridge, MA: Harvard University Press, 2013).
[7] Lonsdaleite, named in honour of crystallographer Kathleen Lonsdale, is a polymorph of diamond.

lead formally used for writing since Roman times. Less surprising was the connection between ‘black lead’ (a residue from the distillation of animal or vegetable matter in a limited supply of air), and the use of the same material to draw the pictograms of cave paintings some 30,000 years ago. Yet this artists’ material was also used to heat iron in metallurgy. What does coal – the fuel of the industrial revolution extracted by the ton from mines all over Europe and in the colonies – have in common with the precious diamond?

In their chemical mode of existence, diamond and graphite are two allotropes: they are made of the same carbon atoms and differ only in the bonds between atoms. However, from an ontographic perspective, they share more than chemical allotropy. From the graphite pencil to diamond-engraving tools and the ‘code of life’ based on a carbon backbone, from the periodic table to the ‘carbon footprint’, from the carbon black tattoos of Ötzi the Iceman (5200 years ago) to the ‘tons of carbon equivalent’, measuring the global warming and to radiocarbon dating (^{14}C), carbon is linked with the action of scripting (*graphein*). It exists in inscriptions, for conservation, standardization and circulation. Human history is written in carbon. If it is true that human civilization began in prehistory with the mastery of fire, then carbon, by its very name – derived from the Latin root *carbo*, ‘burnt’ – connects nature and culture. If it is true that history began with writing, then carbon in its form of graphite kicked off cultural history. Nowadays carbon traces allow humans to read their history against the background of a wide spectrum of timescales, ranging from a few years to geological eras.

This essay presents the various modes of existence of carbon as its *signatures*. It lends a voice to its multiple *personae* and allows them to write their own narratives. Just as the Portuguese poet Fernando Pessoa had various *heteronyms* sign his works of fiction, carbon has several signatures for writing ever-new scripts and telling various stories that interweave human history, natural history and cosmic processes. To what extent could we consider the name ‘carbon’ as a multiplicity of heteronyms, each having its own signature? In considering carbon as a scribe with multiple identities, this chapter will emphasize the ways in which each *persona* of carbon interacting with our material and symbolic practices create togetherness and sketch the lines of our common world.

Carbon as Mephitis

In *Aeneid*, the Roman poet Virgil describes the valley of the river Asanto in Campania as an entry to hell.

> In midst of Italy, well known to fame
> There lies a lake, Amsanctus is the name
> Below the lofty mounts: on either side
> Thick forests the forbidden entrance hide.
> Full in the centre of the sacred wood
> An arm arises of the Stygian flood,
> Which, breaking from beneath with bellowing sound,
> Whirls the black waves and rattling stones around.

Here Pluto pants for breath from out his cell,
And opens wide the grinning jaws of hell.
To this infernal lake the Erinye flies;
Here hides her hated head, and frees the lab'ring skies. [8]

The foaming marsh, named *la Mefite* by local peasants after a fury called Mephitis,[9] has the largest natural non-volcanic CO_2 emission rate ever measured on Earth (about 200 tons per day). Virgil's scary description echoed and further propagated legends about the evil and pestilent nature of Mephitis. While the site is still considered potentially hazardous, especially in the absence of wind,[10] the shepherds of the neighbourhood have continued to bring their sick sheep to *la mefite* during transhumance in order to cure them. Between Chthonian depths and Ouranian vapours, life and death, Mephitis 'stands in the middle'.[11] She was a kind of *pharmakon*, evil and remedy at once, as well as a scapegoat. In the course of time, this ominous exhalation has been named 'mephitic air', 'pestilential vapour', 'lethal spirit', 'deadly spirit', 'fixed air', 'aerial acid', 'acid air', 'chalky acid', 'sylvester spirit', or simply, 'gas'. In fact CO_2 is the archetype of the notion of 'gas'.[12] This term, coined in the seventeenth-century by Joan Baptista van Helmont refered to, both a deadly substance and a principle of life: on the one hand, it is a kind of *pneuma* animating a body; on the other, because of its impetuous and elusive character, it turns into a dangerous killer when released.

To be sure, the reform of the language of chemistry promoted by French chemists in 1787, was a serious attempt to purify carbon from the 'archaic symbols' conveyed by Mephitis's avatars. The name 'acide carbonique' erased the connotations of life and death, of good and evil, borne by the ancient denominations of CO_2. Let us see whether Mephitis's formidable power has been defeated or merely concealed by the *mêlée* of more modern carbon heteronyms.

Carbon as a Standard

In nineteenth-century chemistry, carbon provided a taxonomic scheme that allowed chemists to establish order within the crowd of individual substances. When chemists undertook to set up a classification of chemical elements, carbon played a decisive role in defining what was to be classified. Dmitiri Mendeleev used the case of carbon as a kind of template to define the concept of chemical elements as distinct from that of simple substances. The allotropic forms of carbon (diamond, graphite and coal) are exemplars of the concrete stuff of simple substances.

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8 Virgil, *Aeneid*, VII, on pp. 562–71. Trans. John Dryden (New York: P.F. Collier and Son, 1909).

9 A. Di Lisio, F. Russo and M. Sisto, 'Un itinéraire entre géotourisme et sacralité en Irpinie (Campanie, Italie)', *Physio-Géo*, 4 (2010) pp. 129–49, on p. 142. Furies or Erinyes are mythical entities personifying revenge and persecution.

10 In 1986, a giant CO_2 bubble explosion killed all animals – including hundreds of humans – in an area of a few square kilometres around the lake Nyos, in Cameroon's volcano region. The inhabitants attributed this stealth kill to Mazuku, the God of lakes. See J. Soentgen, 'On the history and prehistory of CO_2', *Foundations of Chemistry*, 12:2 (2010) pp. 137–48.

11 A. Di Lisio et al. , 'Un itinéraire entre géotourisme et sacralité en Irpinie, on p. 143.

12 J. Soentgen, 'On the history and prehistory of CO_2'.

> A simple body is something material, a metal or a metalloid, endowed with physical and chemical properties. The idea that corresponds with the expression simple body is that of the molecule […]. By contrast, we need to reserve the name element to characterize the material particles that constitute the simple bodies and compounds and that determine the manner in which they behave in terms of their physical or chemical properties. The word element should summon up the idea of the atom.[13]

While simple substances come into existence as concrete and physical entities at the end of a process of analysis and purification, elements are the material but invisible parts of simple and compound bodies. Carbon is a hypothetical abstract entity since it can never be isolated – in stark contrast to diamond (pure carbon) and anthracene (90% pure carbon). Nevertheless the element carbon is real and identifiable by a positive individual feature: its atomic weight. For Mendeleev the atomic weight was the signature of elements. The signature of carbon was 12.

How can atomic weight be quantified when it is impossible to measure the weight of atoms? The system of atomic weights had to be set up on the basis of relative and conventional values. Carbon again played a decisive role in this process by being chosen as the standard in the mid-twentieth century. The earliest systems of atomic weights based on a conventional standard unit H=1 (hydrogen equals 1) or O=16 (oxygen equals 16) no longer worked after the discovery of isotopes. For example, physicists attributed the value 16 to one single isotope of oxygen, while chemists attributed that same value 16 to the whole range of oxygen isotopes 16, 17 and 18. In 1959-1960, the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) agreed to put an end to this troublesome discrepancy by electing the isotope carbon-12 as the standard reference for determining the atomic mass of all other elements. In 1961, an IUPAC convention defined the Dalton or UMA (Unified Atomic Mass Unit) as one-twelfth of the mass of an atom of ^{12}C Carbon thus acted as a diplomat, a mediator to settle a conflict between chemists and physicists.

It also provided the standard for defining the concept of mole. A mole, or N, (Avogadro's number) refers to the amount of substance of a system, which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12 (6.0220451023). N atoms of ^{12}C have a mass of 12 grams. As the basis for mole, carbon acts again as mediator. This time it mediates between the nanoworld of atoms and molecules and the macroscopic world of human operations on matter, making the chemists' life easier.[14]

Carbon as Substance

The periodic system has been set up by Mendeleev in an effort to discover the unique

[13] Mendeleev, 'The relation between the properties of the atomic weight of the elements', 1871, reprinted in H. M. Leicester and H. S. Klickstein (eds.), *Sourcebook in Chemistry 1400–1900* (New York: Dover, 1953). on p. 693.

[14] C. Buès, *Histoire du concept de mole : à la croisée des disciplines physique et chimie* (Lille : Atelier national de reproduction des thèses, 2001).

and general law governing the irreducible diversity of chemical phenomena. This law stated that the properties of simple and compound substances are a periodic function of the value of the atomic weight of elements.

Mendeleev's emphasis on the centrality of elements was maintained and reinforced in the early twentieth century with the discovery of isotopes. Carbon came to be considered an underlying substratum (*sub-jactum*) that persists through chemical changes. This substantialist approach was conveyed by Friedrich Paneth, a German chemist who demonstrated that radio-elements could not be isolated from the most common isotope by chemical means, and thus could be considered as true elements. In trying to identify the mode of existence of what is preserved unchanged through chemical metamorphoses, Paneth adopted a substantialist stance through his distinction between 'basic substance' (*Grundstoff*) and 'simple substance' (*einfacher Stoff*).[15] '*Stuff*' thus became a central concept in the philosophy of chemistry[16], a metachemically refined version of the metaphysical 'substance'. Indeed Paneth did not come up with the typical metaphysical notion of substance, as an undifferentiated substratum of matter identified by primary qualities such as extension and impenetrability.[17] Instead of trying to reduce qualities to quantity, as philosophers did in the mechanical tradition, Paneth clearly assumed that chemists could not reduce secondary qualities to primary qualities as they had to assume the persistence of qualities in compounds.

In order to identify the 'something' that remains unchanged through chemical changes, Paneth revived the Aristotelian notion of *hupokeimenon* as a basic and general level of reality underlying the various particulars accessible to sense perception. Whereas the basic substance (G*rundstoff*) has no existence in space and time, simple substances are unique events located *hic et nunc.* Paneth was thus in a position to answer Aristotle's question: 'What is it (*to esti*) ?' And he provided a dual answer, as Aristotle did: it is both a singular phenomenal entity, an individual that you can see and point your finger at (*ek-keimenon*) *and* a universal substrate (*hupokeimenon*) underlying and explaining particular and changing phenomena. Carbon as substance connects modern chemistry with ancient metaphysics.

Carbon as Material

In chemical textbooks carbon appears as a substance because of the ontological priority granted to atoms. However in the material world around us, artisans and engineers do not find carbon atoms. Nature affords carbon molecules and compounds, that can be

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[15] F. Paneth, 'The epistemological status of the concept of element', *British Journal for the Philosophy of Science*, 13 (1962), pp. 144–60.

[16] K. Ruthenberg and J. van Brakel (eds), *Stuff. The Nature of Chemical Substances* (Würzburg: Verlag Königshausen & Neumann, 2008)

[17] In this respect Paneth's notion of *Grundstoff* could not be a target for Bachelard's criticism of the metaphysical view of substances, which he contrasted to the rich metachemical notion forged through a process of realisation. Although Bachelard would object to Paneth's concern with conservation, he could not reproach him for having an intellectual view of matter as a generic entity. Such an impoverished notion, instantiated in Descartes' meditation on a piece of wax, was in Bachelard's view the counterpart of his substantialist view of the cogito. G. Bachelard, *La Philosophie du non. Essai d'une philosophie du nouvel esprit scientifique*, 1940 (Paris: Presses Universtaires de France, 1988), on p. 53. Engl. tr. *The Philosophy of No. A Philosophy of the New Scientific Mind* (New York: The Orion Press, 1968), on p. 45.

used as materials. Many of them have played key roles in human industries since prehistory. For instance, bitumen – a hydrocarbon containing 80% carbon and formed from plankton slowly accumulated in sedimentary basins – was already used by Ancient Egyptians for coating roads, boats, canals, dams and tanks. Asphalt – a mixture of bitumen and aggregates which coated the streets of London and Paris around 1820 – was used by seventeenth-century engravers for etching and by painters to bind their pigments. Coal and bitumen have also long been known for their antiseptic properties: the Phoenicians carbonized the wooden barrels of trading ships in order to preserve drinking water on their long journeys at sea, while the Egyptians treated teeth cavities with a mixture of bitumen and clay. Carbon fibres, which are widely used today in the manufacture of composites due to their remarkable properties – resistance, flexibility and light weight –, enjoyed prior industrial success in light bulbs, when Edison and Swan used filaments obtained by the 'carbonization' of cotton and bamboo.

Such industrial uses of carbon materials did not follow from the theoretical understanding of carbon's atomic structure and of the carbon-carbon bond. Rather, the potential uses of hydrocarbon molecules were gradually explored in a complex process of de-contextualization and re-contextualization of pharmacists' and manufacturers' knowledge and know-how about carbon materials.[18] Carbon materials bridge the gap between the phenomenal world of technological applications and the theoretical world of molecular structures and models.

Carbon as Skeleton

The identification of the unique atomic structure of carbon (tetrahedral with four valence electrons) and its wide-ranging binding capabilities (C–C, C=C, C≡C, C–H, etc.) accounts for the remarkable *dispositions* of carbon (what it is capable of): stability, resistance, and combinatory potential to form innumerable compounds.

These dispositions have been put to work in creative processes, both in nature and in art. In nature, biomolecules such as DNA, RNA, proteins, carbohydrates and lipid membranes are all structured around a strong carbon backbone.[19] Significantly, this backbone resists the current ambition of synthetic biologists to re-engineer life at the molecular level and redesign DNA. Whereas synthetic biologists are able to change the pairs of bases that carry the genetic information and recombine them in all possible ways, it seems that they cannot fix 'God's mistakes', that is, changing the backbone itself with its repeating negative charges (which look odd if not absurd to a synthetic chemist).[20]

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[18] A. S. Travis, W. J. Hornix and R. F. Bud, *British Journal for the History of Science*, 25:1 (1992), pp. 91–111; S. Tomic, *Aux origines de la chimie organique – Méthodes et pratiques de pharmaciens et des chimistes* (1785-1835) (Rennes: Presses Universitaires de Rennes, 2010).

[19] We humans can be described as a compound of carbon-based molecules $C_{E27}H_{E27}O_{E27}N_{E26}P_{E25}S_{E24}Ca_{E25}K_{E24}Cl_{E24}Na_{E24}Mg_{E24}Fe_{E23}F_{E23}Zn_{E22}Si_{E22}Cu_{E21}B_{E21}I_{E20}Sn_{E20}Mn_{E20}Se_{E20}Cr_{E20}Ni_{E20}Mo_{E1}9Co_{E1}9V_{E18}$ (with E meaning "exponent 10") according to the latest averaged estimation of the "human molecule" formula. See Thims, Libb, M., *The Human Molecule* -Morissville NC: Lulu Inc, 2008).

[20] S. Benner, 'Act natural', *Nature*, 427: 9 (2003) p. 118; S. Benner, F. Chen and Z. Yang, 'Synthetic biology, tinkering biology and artificial biology: A Perspective from chemistry', in P. L. Luisi and C. Chiarabelli (eds), *Chemical Synthetic Biology* (Weinheim: Wiley, 2011) pp. 69–106.

In the realm of technology, millions of organic chemical compounds synthesized by the chemical industry are also made of a carbon backbone, albeit less complex than those made by nature. Whether natural or artificial, organic compounds are the products of the structural combinatorial game enabled by carbon binding dispositions. Thus synthetic products, usually presented as products of human design driven by social demands, are also examples of the actualization of carbon dispositions. Underlying the traditional divide between the natural productions of life and the highly artificial processes of industry runs an invisible thread, an elegant, robust, but largely unnoticed microstructure: the carbon backbone.

Carbon as Surface

Over the past twenty-five years, carbon has been the star of materials research, generating more and more exotic allotropes: nanotubes[21], fullerenes,[22] graphene,[23] nanobuds,[24] nano-onions,[25] nanotori,[26] nanocones, nanohorns,[27] nanobamboos,[28] nanoribbons,[29] and so on. This weird menagerie has garnered many awards: the 1996 Nobel Prize in Chemistry for the fullerenes, the 1998 Kavli Prize in Nanoscience for carbon nanotubes, and the 2010 Nobel Prize in Physics for graphene, the individual sheet of graphite. The new avatars of carbon allotropes have prompted the coming into being of a kind of parallel world, which is invisible yet simultaneously amply visible in the media: the 'nanoworld'. Once again, after the great expectations generated by nineteenth-century synthetic chemistry, carbon appears as a cornucopia of futuristic products: screens, batteries, organic electronics, ultra-fast computers, ultra-thin sensors, traps for pollutants – and it even promises an elevator into space using a giant cable made of braided carbon nanotubes! However, these materials and their technoscientific mode of existence are far more bizarre and fascinating than their potential – and perhaps speculative – applications.

First, since these structures can be considered either as tiny crystals or as giant molecules, they challenge the boundary between organic and mineral. Second, their

[21] S. Iijima, 'Helical microtubules of graphitic carbon', *Nature*, 354:6348 (1991) pp. 56-58.

[22] H. W. Kroto, J. R. Heath, S. C. O'Brien, R. F. Curl and R. Smalley, 'C60: Buckminsterfullerene', *Nature*, 318:6042 (1985), on pp. 162–3.

[23] A. K. Geim and K. S. Novoselov 'The rise of graphene', *Nature materials*, 6:3, (2007) pp. 183–91.

[24] A. G. Nasibulin, V. P. Pikhitsa, H. Jiang, D. P. Brown, A. V. Krasheninnikov, A. S. Anisimov, P. Queipo, A. Moisala, D. Gonzalez, G. Lientschnig, A. Hassanien, S. D.. Shandakov, G. Lolli, D. E. Resasco, M. Choi, D. Tománek and E. I. Kauppinen, 'A novel hybrid carbon material', *Nature Nanotechnology*, 2:3 (2007) pp. 156–61.

[25] A. S. Rettenbacher, M. W. Perpall, L. Echegoyen, J. Hudson and D. W. Smith Jr., 'Radical addition of a conjugated polymer to multilayer fullerenes (Carbon Nano-onions)', *Chemistry of Materials*, 19:6 (2007) pp. 1411–17.

[26] B. J. Cox, J. M.. Hill, 'New Carbon Molecules in the Form of Elbow-Connected Nanotori', *The Journal of Physical Chemistry C*, 111:29 (2007), pp. 10855–60.

[27] S. Iijima, M. Yudasaka and V. H. Crespi, 'Single-wall carbon nanohorns and nanocones', in *Carbon Nanotubes, Topics in Applied Physics*, 111 (2008) pp. 605–629.

[28] J. Koltai, A. Rusznyák, V. Zólyomi, J. Kürti and I. László, 'Junctions of left- and right-handed chiral carbon nanotubes – nanobamboo', *Physica Status Solidi (b), Special Issue: Electronic Properties of Novel Materials*, 246:11–12 (2009), pp. 2671–74.

[29] L. Jiao, L. Zhang, X. Wang, G. Diankov and H. Dai, 'Narrow graphene nanoribbons from carbon nanotubes', *Nature*, 458 (2009), pp. 877–80; R. Fasel et al. , 'Atomically precise bottom-up fabrication of graphene nanoribbons', *Nature*, 466:7305 (2010) pp. 470–473.

combinatorial potential no longer involves populations of molecules in chemical reactions; it rather refers to a game of construction involving the assembly of individual carbon molecules. Third, structure and properties matter less than the *functions* to perform (mechanical, electronic, photonic, chemical, magnetic). Finally, structures are viewed as configurations in an indefinite set of transformations.

Since these new avatars of carbon allotropes are single or multi-layered configurations of individual graphite sheets, graphene stands as the matrix of all of them, at the frontiers of matter. It is the thinnest and the strongest material known to exist.[30] Its electrons behave like massless particles, travelling at a much higher speed than in silicon. Graphene is also flexible, light absorbent, and is a chemical reactant. It is indefinitely malleable: it can be cut, bent, folded, rolled or zipped into a tube or a cone, just as in origami and kirigami art.[31] Graphene blurs the metaphysical divide between substance and phenomena, between primary and secondary qualities.

In this technoscientific style of research, carbon is less a source of dispositions (i.e. substantial and permanent properties waiting to be actualized) than a source of *affordances*, i.e. relational and functional properties that can only be performed and instantiated by the combination of material dispositions and intentional contrivance.[32] Indeed, graphene makes it possible to direct or confine electrons and photons; to change the polarity of a spin; to accelerate processes; to encapsulate molecules; to provide experimental systems for quantum field theory or 2D physics; to save information bits, or to make sensors with the help of grafted molecules-probes. In brief, graphene affords an entire playground, displayed in the thousands of papers and patents relating to graphene that appeared in 2010.

Graphene is less the surface of something, than a 'surface in itself', made of nothing else, a surface without bulk. Unlike carbon as substance, carbon as a pure surface does not stand as a permanent substratum securing an ontological identity at a deeper level of reality. Rather, it signs a new script of technoscientific research where superficiality matters.

Carbon as Memory / Carbon as Fire

'Burning buried sunshine',[33] this sounds like a crazy project. It is no more a playful construction game with thin carbon sheets, but rather a mass destruction of deeply buried underground carbonaceous materials. The fate of fossil hydrocarbons exemplifies another of the interactions between the material properties of carbon and human history and politics. The layers of biomass accumulated over millions of years as sediments of hydrocarbons are like a repository of the past. They make up the material memory of life on Earth. By massively resorting to the energy of this 'buried sunshine', humans are

[30] N. Salvage, 'Super carbon', *Nature*, 483:7389 (2012), pp. S30–1.

[31] J. García, R. Esparza, R. Perez, 'Origami construction of 3D models for Fullerenes, Carbon Nanotubes and Associated Structures', *The Chemical Educator*, 14 (2009) pp. 221–4.

[32] R. Harré, 'The Materiality of Instruments in a Metaphysics for Experiments', in H. Radder (ed), *Philosophy of Scientific Experimentation* (Pittsburgh: University of Pittsburgh Press, 2003), pp. 19–38.

[33] J. S. Dukes, 'Burning Buried Sunshine: Human Consumption of Ancient Solar Energy', *Climatic Change*, 61:1–2 (2003) pp. 31-44.

consuming this memory at a rate of a few centuries per year. According to Alain Gras, the 'choice of fire' is the signature of our civilization, with its 'cowboy economy' and massive exploitation of fossil fuels.[34] The peculiar set of relations that have been set up and reconfigured between the material properties of carbon, international finance, expertise and democracy is well described in Timothy Mitchell's essay *Carbon Democracy*. Coal played a critical role in forging democracy by encouraging social movements while oil has shaped and continues to shape the politics of Western and Middle East countries.[35]

Carbon's etymology, however, suggests that its association with fire is not limited to this contingent history. Fire drove the ontogenesis of carbon as a chemical element since it has been identified through the combustion of diamond in the experiments conducted by Lavoisier, Macquer and Guyton de Morveau in Paris and by Tennant in London.[36] These experiments demonstrated that burning a certain amount of diamond and burning an equivalent mass of charcoal released the same volume of 'fixed air' (carbon dioxide). Moreover, the association between carbon and fire does not necessarily mean irreversible consumption. Nineteenth-century chemists investigating the circulation of carbon through the three realms of nature – mineral, plant and animal – described animals as combustion engines releasing carbon dioxide into the atmosphere, while plants 'fix' the carbon and release oxygen. Living beings do not 'burn' calories as an internal combustion engine burns gasoline. Instead, they convert calories into 'soft energy' (known today as adenosine triphosphate) and then reuse much of the waste. Ashes can be used as a fertilizer and can participate in cosmic cycles. Jean-Baptiste Dumas's 'chemical statics of organized beings' is reminiscent of carbon exhalations as Mephitis, dispensing Life and Death.[37] Such 'archaic' symbols of carbon survive in today climate science and policy.

Carbon as Equivalent

In their efforts to mitigate the climate disruptions induced by the use of carbon-fire, humans have once again selected carbon as a standard. Carbon provides the 'rate of exchange' of all greenhouse gases (GhGs) according to their global warming potential (GWP),[38] just as gold or the US dollar did for currencies. And carbon dioxide, the historical archetype of all gas, became 'carbon dioxide equivalence' (CO_2eq), the reference for devising 'green' markets and environmental finance devices. While carbon

[34] A. Gras, *Le choix du feu* : *Aux origines de la crise climatique* (Paris: Fayard, 2007).
[35] T. Mitchell, *Carbon Democracy. Political Power in the Age of Oil* (London, New York: Verso, 2001)
[36] A. L. Lavoisier, 'Sur la destruction du diamant par le feu' (1772) in *Opuscules physiques et chimiques. Œuvres* vol. 2 (Paris, Imprimerie impériale, 1862), pp. 591–616; S. Tennant, 'On the nature of diamond', *Philosophical Transactions of the Royal Society*, 87 (1797), pp. 123–127.
On this troublesome episode, see the historical work conducted by Christine Lehman, 'What is the "True" Nature of Diamond?' *Nuncius*, 31:2 (2016) pp. 361–407 ; 'À la recherche de la nature du diamant: Guyton de Morveau successeur de Macquer et Lavoisier'. In *Annales historiques de la Révolution française* 1 (Armand Colin, 2016), pp. 81–108.
[37] J. B. Dumas, *Essai de statique chimique des êtres organisés* (Paris : Fortin, 1842), reprint in *Leçons de philosophie chimique* (Bruxelles : Culture & civilisation, 1972).
[38] Saying that 'methane has a GWP of 23' means that 'methane creates 23 times more greenhouse effect than an equal volume of CO_2 would do over the same period of time'. Thus, to obtain the CO_2eq of a certain amount of methane, one multiplies the number of tons emitted by its GWP.

trading is meant to get the economy back down to earth, it actually turns carbon into a speculative product and renders carbon exchanges soluble into those of our current dematerialized capitalism. All that is solid…

As all equivalents, carbon affords *commensurability*. It allows quantitative comparison between various gases[39] and between heterogeneous human actions (How much carbon equivalent does your wedding party weigh? What is the carbon footprint of your alimentary diet?) Carbon globalizes the ecosystem at the planetary scale. Such system of equivalence allows considering the global ecosystem and the global economy like two *oikoï* exchanging carbon. Carbon thus bridges natural processes and human enterprises. It even allows equating present and future GhGs emissions or reductions. For instance planting trees, replacing a fuel generator by a wind turbine are supposed to compensate for global CO_2 emissions. A certain amount of GhGs emitted in one part of the world is thought to balance an equal reduction in another part of the world, etc.[40]

Carbon markets are based on such equations.[41] The commensuration achieved by the carbon-equivalent is turned into a mechanism of *compensation*, which has been compared to the system of *indulgences*, the 'market of pardon' once established by the Catholic Church.[42] An activity emitting excess gases today is declared 'carbon neutral' on the assumption that the excess will be 'neutralized' when the trees have matured in the future. This alleged neutrality depends not only on conjectures about the future but also on counter-factual estimations of the increase of emissions if the project had not been achieved.[43] Buzzwords such as 'carbon neutrality', 'decarbonizing industry' or 'zero-carbon planet' make of carbon the 'bad guy'. This demonization of carbon revives the ancient identification of carbon dioxide with malefic power.

Carbon trading schemes wrongly put the blame on carbon itself. The problem is not that there is too much carbon (though there is, of course, too much CO_2 in the atmospheric air). In fact, the system of compensation nurtures the social construction of ignorance.[44] It provides means for endlessly postponing effective measures aimed at reducing emissions. By dissociating actions from their consequences, it tends to dissolve the urgent issue of climate change into counterfactual and abstract speculation. It also serves to disconnect the present from the future by persuading people that they can be 'carbon neutral' and consequently not indebted to future generations, instead of

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[39] For instance, one ton of methane weighs 23 tons of CO_2eq or 6.27 Carbon equivalent. To convert CO_2eq into Carbon equivalent, one multiplies it by the approximate mass of carbon atoms contained in one ton of CO_2 that is, 0.2727. Thus, for methane: $23 \times 0.2727 = 6.2721$. In this respect, the role of Carbon eq in carbon accounting is analogous to the role of the mole in chemistry.

[40] A. Fragnière, *La compensation carbone : illusion ou solution ?* (Paris: Presses Universitaires de France, 2009).

[41] D. MacKenzie, 'Making things the same: Gases, emission rights and the politics of carbon markets', *Accounting, Organizations and Society*, 34:3–4 (2009) pp. 440–55.

[42] D. Adam, 'You feel better, but is your carbon offset just hot air?', *Guardian*, 7 October 2006; K Smith, *The Carbon Neutral Myth, Offsets indulgences for you climate sins* (Amsterdam: Carbon Trade Watch, 2007).

[43] L. Schneider, 'Is the CDM fulfilling its environmental and sustainable development objectives? An evaluation of the CDM and options for improvement' (Berlin: Öko Institute, 2007). http://www3.oeko.de/oekodoc/622/2007-162-en.pdf (accessed September 2014)

[44] L. Lohmann, 'Carbon Trading, Climate Justice and the Production of Ignorance: Ten examples', *Development*, 51 (2008), pp. 359–65.

considering how human activities have disrupted the carbon cycle over million of years as described by paleo-climate scientists.

The problem is rather that our consumption of hydrocarbons is *interrupting the carbon chain,* 'freezing' the carbon cycle. By consuming centuries of 'buried sunshine' per year, we create a chasm between the historical time of human activities and the geological and biological timescales. While carbon trading claims to bridge the gap between the linear timeline of economic growth and the cyclic times of carbon exchanges, it actually increases the gulf between these heterogeneous 'timescapes',[45] and neglects the work of composition that these multiple (and not necessary harmonious) temporalities require. The alledged 'bad guy' that would have to be 'neutralized' or 'sequestered' should rather be rescued, because life depends on it. After all, carbon is life – not life in its 'essence', but life it its diversity, profusion and interdependence.

Toward an Ontography of Carbon

Carbon signs the rich narrative of a *persona* always on the move, always binding with itself as well as with others. Endlessly metabolized, exchanged, fixed and released, it forms as many heteronyms as there are ways for carbon to be an object. In surveying the multiple identities of carbon and treating them as heteronyms – real signatures of fictitious *personae* – this essay sought to highlight three major features of technoscientific objects.

First, the unbounded productivity of technoscientific objects may be due to their multiple identities. Carbon is much more than a scientific object. Without questioning the central importance of the definition of carbon as a chemical element, we argued that it is only one of the many ways for carbon to sign its name (as a permanent substrate underlying various phenomenological appearances). The hierarchy of levels of reality suggested in this metaphysical perspective, even when it is 'metachemically' refined in order to guarantee the notion of chemical individuality, results from the reductive entrenchment of many modes of existence into a single one. On the contrary, our approach was to spread and to maintain the constellation of carbon's modes of existence while resisting the 'imperialist' temptation to deduce their plurality from one of them.

Is it possible to characterize the scientific approach by the question 'what is carbon?' and distinguish it from a technoscientific approach interested in the question 'what does it do?' This is a false dilemma because both questions overlook the coexistence of multiple modes of being. Neither a substantialist nor an operational definition could take into account the varieties of carbon identities revealed through the circulation of carbon atoms over the centuries. The Janus portrait is only a caricature, which occults multiple personalities. Despite the broad diffusion of scientific names such as 'carbon' and 'CO_2', the purification attempted by means of the reform of chemical nomenclature never succeeded in eradicating the intimate relationship we have with carbon in our vital, technical and symbolic activities. Just as carbon forms many

[45] L. Lohmann et al., *Carbon Trading. A critical Conversation on Climate Change Privatization and Power* (2006), at http://www.thecornerhouse.org.uk/sites/thecornerhouse.org.uk/files/carbonDDlow.pdf (accessed September 2014)

allotropes by binding with itself in specific and different ways, each of its modes of being is able to link up with the others via analogies, metonymies, metaphors, and anaphors. For instance, carbon as a general equivalent in its economical mode plays a role analogous to the role of the mole in its chemical mode of existence, as a standard of commensuration.

Who is carbon, then? Here comes the second feature of this technoscientific object. To use the term Pessoa coined for referring to himself, the scientific name 'carbon' can be considered as the 'orthonym' of a multiplicity of heteronyms, which suggests a proper position, a degree of social 'correctness', but nothing like a deeper ontological level. But the orthonym carbon is neither object nor subject, it is a 'quasi-object' in the sense of Michel Serres.[46] Quasi-objects have no fixed essence; they are defined by the links and connections they create by circulating in local contexts. They build niches and make collectives. A striking feature of quasi-objects is that they continuously cross the boundaries between nature and culture and between the natural and the artificial. The narratives of carbon belong to natural history as well as to human history. Some of its modes of existence have been characterized as mediators, bridging the heterogeneous realms of the inorganic and the organic, of the natural and the synthetic, of ecology and economy. Through exchanges, combinations, uses and re-uses by humans and nonhumans, carbon challenges the hierarchy of ontological levels by creating a sort of bio-pedo-geo-hydro-atmo-cosmo-sphere. Besides carbon is a mediator establishing a common measure between heterogeneous regions of the world. Just as the balance in the hands of Lavoisier,[47] carbon affords commensurability between the smallest and the largest scales, between the mineral, the vegetal and the animal, between the moral and the social, between the economic and the ecological. As a powerful mediating apparatus, carbon also encourages ambitious attempts at controlling the world. The balance of gains and losses, based on static equilibrium, generates a space of illusory rational control and power over the future, instantiated in carbon trading.

Finally, as carbon opens up the 'cosmopolitical' perspective of a common world shared by humans, other living beings and things, what kind of approach is the most appropriate to clarify its ontology? The narratives written by the heteronyms of carbon are at odds with the grand Promethean narrative forged by the champions of nanotechnology, synthetic biology and other ambitious technosciences. 'Shaping the world atom by atom' or re-engineering nature to improve it, are slogans that celebrate the power of human design over nature. Designers like to stress their enhanced capacity to control and shape materials thanks to their access to the molecular level. In their view, materials are no longer a prerequisite for design: fullerenes, carbon nanotubes, graphene are 'materials by design'. This phrase suggests that engineers are emancipated from all constraints of materiality. This essay, by contrast, emphasizes the affordances

[46] M. Serres, *The Parasite*. Trans. Lawrence R. Schehr (Baltimore, London: Johns Hopkins University Press, 1982).
[47] B. Bensaude-Vincent, 'The Balance: Between chemistry and politics', *The Eighteenth Century*, 33:3 (1992), pp. 217–37; N. Wise, 'Mediations: Enlightenment Balancing Acts, or the technologies of rationalism', in P. Horwich (ed.), *World Changes, Thomas Kuhn and the Nature of Science* (Cambridge, MIT Press, 1992), pp. 207–56.

of materiality. As chemist Richard Smalley put it in his 1996 Nobel lecture, carbon has a 'genius wired within it':

> The discovery that garnered the Nobel Prize was the realization that the carbon makes the truncated icosahedral molecule, and larger geodesic cages, all by itself. Carbon has wired within it, as part of its birthright ever since the beginning of this universe, the genius for spontaneously assembling into fullerenes. [48]

The physical and chemical properties of carbon afford opportunities for creating new lives and powerful concepts. Whether robust like the carbon backbone of DNA or delicate like the thin layer of graphene, all heteronyms of carbon are active and reactive in the hands of smart engineers. This is why an *ontography* seems more appropriate than an ontology for carbon. What is the difference?

We choose ontography as a genre for emphasizing the significance of 'graphism' and graphemes, of meaningful material traces printed by objects.[49] Ontography offers a number of advantages. First, as Lynch argues, it is an attempt to dignify a descriptive approach based on empirical study.[50] Ontography deflates the quest for a unique substrate underlying a variety of materials. In stark contrast to ontology, it does not build a grand theory based on a hierarchy of the entities that make up the universe. Just as the term 'ontogenesis', ontography focuses on individual entities. It is compatible with pluralism. It seeks to give a voice to a plurality of beings rather than trying to silence them.

In addition, as an attempt to identify the modes of existence of particular entities, ontography does not assume a causal chain between levels of being. Nor does it single out any level of being. It opens up the possibility for humans to engage with objects as partners, thus co-creating their affordances. This process can be denoted as the 'instauration' of new identities.[51] Finally, ontography allows space for a multiplicity of ontological modes. An entity such as carbon displays many different ways of being an object according to its relations, reactions and circumstances.

In this process, objects are not just materials. We have seen that carbon has become a matter of concern and a matter of affairs. May we suggest that the pattern of relations displayed by each heteronym of carbon has to become a matter of care as well? We would well be advised to take care of its multiple modes of existence in order to better inhabit the common world that we share.

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[48] R. Smalley, 'Discovering the Fullerenes', Nobel Lecture, December 7, 1996, on p. 90 at http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1996/smalley-lecture.html (accessed September 2014).

[49] Jacques Derrida in his deconstructivist analysis of the Western *logos* emphasized its domination over *graphein*, construed as mere tool for the living speech of the soul. By contrast, our use of onto*graphy* is not a rebellion against *logos* and welcomes instead many *logoï* to join the fun. In emphasizing the traces printed or (quasi) written by (quasi) objects, we suggest than we – humans articulating these words – are the storytellers.

[50] M. Lynch, 'Ontography: Investigating the production of things, deflating ontology', *Social Studies of Science*, 43:3 (2013), pp. 444–62. For current use of ontography in archaeology and ethnology see M. Holbraad, 'Ontology, Ethnography, Archaeology: an Afterword on the Ontography of Things', *Cambridge Archaeological Journal*, 19:3 (2009) 431–41.

[51] E. Souriau, *L'instauration philosophique* (Paris: Alcan, 1939).