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Article

Promises, Unpredictability, and Artificial Positivities: Modes of Existence of Certain Chemical Entities

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Abstract:

The materials emerging from chemical laboratories are not fixed essences: they are hybrid entities—entwined with matter, technique, nature, and culture—whose properties are actualized as they circulate through diverse ecologies. From this understanding, we propose a relational philosophical framework to elucidate three conceptual operators that facilitate the comprehension of their modes of existence. First, the "economy of promises": regimes of expectations that drive investments, shape markets, and imaginaries, and often eclipse environmental and social costs. Secondly, "unpredictability": unanticipated effects that emerge when molecules move between contexts. Thirdly, "artificial positivity": the capillarization of psychotropics as they move from therapeutic niches to performance-enhancing instruments, establishing chemically modulated forms of life. From these three operators, we derive essential normative criteria to prevent and counteract certain opaque and deleterious modes of existence of specific material entities produced by the chemical industry. Through this relational perspective, we seek to shift the focus from "what is" to "what might come to be" and "at what cost"; the philosophy of chemistry thereby reinserts into public debate dimensions often absent from purely descriptive or functionalist analyses of chemical entities.

Keywords: Philosophy of Chemistry, Economy of Promises, Unpredictability, Artificial Positivity

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Introduction

Chemistry, beyond investigating and mapping the properties of already known entities, has among its principal objectives the creation of new material bodies. The trajectory of a material entity produced in the chemists' laboratory is not exhausted by its initial characterization but remains in a process of becoming, revealing new facets and effects

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across its distinct temporalities of existence. In this sense, even chemical substances apparently well-characterized at a given moment evade any static definition. Mercury, for example, was for centuries a key material in laboratory and industrial practices—present in thermometers, barometers, and mining processes—before revealing itself as a potent neurotoxin capable of bioaccumulating in food chains and causing environmental disasters such as in Minamata.[3] Titanium dioxide, long regarded as an inert and safe pigment, now occurs in the form of nanoparticles whose reactivity remains insufficiently understood, raising questions concerning cellular toxicity and environmental impact. Even familiar substances such as water resist a fixed definition. Water, typically represented by the formula H_2O, rarely exists in a 'pure' form: it dissolves salts, transports pollutants, participates in acid—base reactions, and in each context acquires distinct properties that can either sustain life or propagate disease. These examples illustrate that the central problem in chemistry lies not solely in characterizing isolated substances but in comprehending their "modes of existence"[4] and circulation within complex material ecologies, traversing temporal scales from the laboratory instant to long-term environmental transformations.

This framework compels us to recognize that chemical substances are not stable and definitive entities, but processes of becoming, whose properties are continually actualized through new relations. As Alfred N. Whitehead (1861–1947) suggested, we must conceive reality as a flow of events rather than as a set of fixed essences. Applied to chemistry, this entails understanding that each substance is constituted not only by its isolated properties but also by the network of relations it establishes with other substances, with the material environments in which it circulates, and with the social contexts in which it is embedded. In this respect, contemporary chemistry distances itself from modern chemistry, whose epistemic horizon was oriented toward the discovery of stable chemical identities and the formulation of universal laws. Today, chemistry must address other specificities: contextual reactivities, emerging risks, indeterminacies, and properties that actualize only relationally. Hence, we argue that a philosophical reflection on the place of chemical knowledge within the sciences, as well as on the capillarization of its products within the "Lifeworld", should adopt a relational perspective that aims to articulate the various "modes of existence" of chemical entities.

This perspective entails understanding chemistry as a field characterized by indeterminacy. As Rheinberger underscores, experimental work not only yields predicted outcomes but also continuously produces the new and unexpected, thereby expanding the realm of the unknown. Every chemical substance synthesized or mobilized in the laboratory bears an excess of as-yet unexplored properties, alongside the potential for unprecedented interactions with other substances. Producing chemical knowledge also entails producing ignorance: an expansion of the domain of indeterminacy and risk that inevitably accompanies each innovation (Rheinberger 1997).

In this article, we propose applying this relational perspective of chemical entities to elucidate three conceptual operators that we consider to contribute to the analysis of certain modes of existence of chemical entities. The first of these, which we designate as

3 The Minamata disaster occurred in 1956 in the eponymous city in Kumamoto Prefecture, Japan. Its cause was the discharge of methylmercury by the Chisso Corporation into coastal waters, which led to the bioaccumulation of methylmercury in marine organisms consumed by the local population, resulting in a severe neurological syndrome—"Minamata Disease"—with hundreds of deaths and thousands affected. The case generated decades of litigation, social mobilization, and debates concerning scientific responsibility, the environmental impacts of technology, and the invisibility of risks within modern production systems (Harada 1995, 1-24).

4 We freely borrow the expression "modes of existence" from Gilbert Simondon without, however, being situated within the same research domain as the French philosopher.

"economies of promises", possesses a comprehensive scope and concerns the creation of new material consumption needs, mobilized by various social sectors such as industry and the economic policies of nation-states. To this end, we examine the case of the creation of aluminum, aiming to clarify the plurality of relations generated through the large-scale use of a metal celebrated as a symbol of modernity. The second conceptual operator we will examine concerns the unpredictability of molecules created by chemists and produced by their industry. We will analyze the case of unpredictability evident in the construction of a technical structure essential to contemporary life: the production of cold (refrigeration). The establishment of a cold chain demands from chemistry the creation of refrigerant molecules that are efficient both thermodynamically and in terms of toxicity and chemical stability. It was within this field of research that unpredictability emerged, with disastrous environmental consequences, as it caused a consequent alteration of the ozone layer that protects our biosphere from ultraviolet (UV) radiation. The third operator we will propose concerns the psychosocial relation created by the capillarization of amphetamines, which exhibit a mode of existence we will identify as "artificial forms of life". We contend that amphetamines serve as a paradigmatic example of how molecules with profound psychotropic effects permeate society in alignment with an era defined by positivity.

Aluminum and the Economy of Promises

The production of aluminum (Al) is connected to the advent of new technologies in metallurgy and electrification, but also to an "economy of promises" (Bensaude-Vincent 2022). These promises are promoted by industry and academia regarding the remarkable properties of this material. Bensaude-Vincent employs the notion of an economy of promises to denote how the potential economic impact shapes research through marketing and advertising campaigns, but also, and primarily, through mounting pressure from funding agencies and industry. In the context of innovation policies oriented towards the future, scientists develop the habit of asserting with greater conviction that their research will yield spectacular results. However, the extravagant promises of new materials have often impeded the anticipation of the environmental and social impacts stemming from their actual production and consumption.

Aluminum is the third most abundant chemical element in the Earth's crust, comprising approximately 8% of it; nevertheless, it scarcely occurs naturally in metallic form, with its compounds predominantly found in the lithosphere. The first sample of metallic aluminum was obtained by a chemical method devised by Friedrich Wöhler (1800–1882), which consisted of treating aluminum chloride with metallic potassium. The quantity of metal produced was small, and the production process was costly, being carried out exclusively in the laboratory. As soon as it chemically came into existence, aluminum was elevated to the status of a noble metal. In addition to its rarity, it possessed, from a technical perspective, properties similar to—and even more intriguing than—those of silver and gold, leading to its use in the manufacture of jewelry. Its principal advocate was equally noble: the French emperor Napoleon III, who designated the metal as a symbol of modernity and French genius at the 1855 Universal Exhibition in Paris (Hachez-Leroy 2022).

Napoleon's support was instrumental in the establishment, from 1860 onward, of a chemical products industry led by Henri Merle (1825–1877), who began producing via a novel method invented by Sainte-Claire Deville (1818–1881). This method substituted metallic potassium, previously used by Wöhler, with metallic sodium, and replaced aluminum chloride with a mineral revealed to be rich in alumina: bauxite. This initiative marks the foundation of the Pechiney Company, one of the industries that would dominate the aluminum market throughout the twentieth century (Marty 2006).

However, for aluminum to become a metal of promise, two indispensable components for its large-scale production had to come into play: electricity and electrification. Without electricity and its large-scale production via the earliest hydroelectric power plants, aluminum would have been a metal without a future. Similarly, the history of electrification across multiple sectors of society is inseparable from the industrial history of this metal. The cheaper and more available the electricity supply, the cheaper aluminum became and, consequently, more attractive than other metals. This connection was established by a novel technical process for obtaining aluminum through the electrolysis of a fused mixture of bauxite and cryolite (Na_3AlF_6), patented independently in 1886 by two engineers, the French Paul Héroult (1863–1914) and the American Charles Hall (1863–1914). Broadly speaking, the process consists of the reduction of calcined alumina to aluminum, which takes place in cells or electrolytic pots through which a direct electric current is passed. The metal deposits at the cathode (negative pole), while the oxygen deposits at the anode (positive pole), which is made of graphite and reacts with oxygen to produce carbon dioxide (CO_2), one of the primary gases contributing to the greenhouse effect. These production protocols for alumina and "electrolytic" aluminum remain in use to the present day (Laparra 2012).

The vast disparity in price and symbolism between "chemical" aluminum and "electrolytic" aluminum poses a significant challenge for museum curators, collectors, and art historians. How does one distinguish an object conceived as valuable—found in medals, jewelry, and decorative items—from another made of the same material but produced when its commercial value was markedly lower and devoid of symbolic associations with power? In this instance, aluminum possesses a dual identity, acquiring entirely distinct social, political, economic, and aesthetic meanings depending on whether it is regarded as "chemical" or as "electrolytic." One of the techniques employed to resolve the problem involves measuring impurity levels caused by the presence of metals such as iron, manganese, or lead, which were significantly higher when the chemical procedure was still in use. This enables stakeholders to determine with greater certainty the identity of the aluminum used in the object under analysis (Bourgarit and Plateau 2005).

However, the reduction in production costs alone was insufficient to popularize the use of the new metal, as the creation of commercial demand was also necessary. It was only amid the instability in copper production during the 1890s that aluminum had the opportunity to become a substitute material. Its properties were substantial, including low density (2.7 g/cm^3), high electrical and thermal conductivity, good resistance to atmospheric corrosion, high reflectivity of light and heat, and considerable mechanical plasticity, which enables it to be formed into sheets, wires, plates, or blocks. Thus, the reduction in production costs had to be accompanied by the promotion of these physicochemical properties to gradually convince industrialists in various productive sectors to replace traditional materials with the new material (Hachez-Leroy 2007).

This economy of promises led to the substitution of older materials such as iron, copper, and wood and was responsible for the social diffusion of aluminum, since, whether in its pure state or as metallic alloys, it began to be used in the manufacture of household utensils as well as equipment for the automotive and aerospace industries. Aluminum became a symbol of modernity, lightness, and speed—qualities that still constitute its hallmarks—and the metal symbolizing the future. This was also reflected in the social sphere, for with the advent of mass tourism and amateur sports practices, the aluminum industry began to produce components used in bicycles and skis, thereby reinforcing its image of modernity. Metallic aluminum, whose existence is owed to electricity, was also associated with it in the conception of a technological innovation—the electric car—such as the model designed during the Second World War by the French engineer Jean-Albert Grégoire (1899–1992) (Pehlivanian 2009; Pérez 2012).

The availability of aluminum as a substitute and innovative material depended, in addition to an industrial process and a marketing campaign, on the organization of industries devoted to its production and their political, economic, and social relations with international markets. The complex financial structure encompassing the entire production cycle characterized a distinctive economic model within the metal market. From its inception, aluminum production was vertically integrated, requiring producers to control bauxite deposits and secure a substantial electricity supply. This also necessitated the establishment of new transportation routes, including the construction of roads, railways, and ports in regions previously unexploited by the capitalist economy. Given the uneven distribution of these resources, the aluminum industry emerged with the objective of forming multinationals by concentrating capital and reshaping, or even destroying, natural landscapes as well as ecological and social contexts (Sheller 2014).

It was the first industrial sector to establish a cartel, not solely to regulate prices—since production cost was not the only factor considered in the availability of the new metal—but also to ensure that aluminum prices were not dictated by metal market traders, but rather determined by the industry in response to the demands of other supply chains. This economic-productive mechanism caused the price of aluminum to remain stable for nearly a century, with production growth exceeding 10% per year. The cartel was controlled by major companies of the era, such as Alcoa, Alcan, Pechiney, Bayer, Reynolds, and Alusuisse, while smaller entities, such as the Brazilian Aluminum Company (CBA), founded in 1955 by Companhia Votorantim, were subjected to these rules under the threat of being absorbed by one of these giants (Holloday 1988; Bertilorenzi 2015).

However, in 1978, a profound transformation took place in the aluminum market. From that point onward, the metal began to be quoted on the London Metal Exchange, the world's most significant market for non-ferrous metals, accounting for approximately 95% of transactions. This marked the financialization of the trade and production of the metal, as the LME transformed physical products into long-term financial assets. This disruption in the aluminum market had multiple causes, including the 1970s oil crisis, alongside the entry of new actors such as China, Australia, Russia, and Brazil, and also owing to a tendency toward financialization within the capitalist system that would intensify in subsequent decades. Historically vertically integrated, the aluminum industry underwent profound transformations from the 1980s onward, marked by successive corporate restructurings and changes in majority shareholders, resulting in the disappearance of most former brands that had been nearly synonymous with aluminum production. Thus, the economic-financial model of aluminum production divides into two periods: one characterized by price stability, and another that situates the aluminum industry within the transformations of the capitalist economy, whose watchwords from the 1980s onward became liberalism and the privatization of state-owned companies (Mouak 2020).

In bringing this "metal of modernity" to life, the proponents of an economy of promises often sought to obscure the ecological and human impacts in the regions mobilized for its production. The displacement of large quantities of materials and the enormous energy required leave profound traces both in the biomes and in the human communities inhabiting them. Because vertical integration demanded control over all production stages, the depletion of bauxite reserves in Europe and the United States compelled multinationals to establish themselves in regions rich in this ore and, preferably, with electricity available nearby. This model, for instance, prompted some companies to develop projects exploiting the bauxite reserves located in the Brazilian Amazon, primarily in the deposits of the state of Pará. In 1979, the Brazilian government decreed that for twenty years, the price of electricity would be pegged to the international price of aluminum and could not exceed 20% of its production cost. To further incentivize the exploitation of this resource by multinationals, the Tucuruí hydroelectric plant was inaugurated in 1984 on the Tocantins River, the largest built on national soil, which has since dedicated approximately 65% of its output to the bauxite-alumina-aluminum production chain (Fearnside 2015).

These favorable conditions attracted multinationals, but the local populations derived no benefits. In fact, they were profoundly affected by the arrival of these creators of the "metal of modernity": flooded regions caused the displacement of riverside populations and the inundation of indigenous peoples' lands, as well as alterations in navigation routes—the primary mode of transportation in the region. The lessons from the environmental and human impacts of the implementation of the Tucuruí plant and the production of Amazonian aluminum appear not yet to have been assimilated by decision-makers within the Brazilian State.[5]

In summary, aluminum possesses multiple modes of existence: geological/mineral, noble metal and symbol of power, modernity, and technological innovation; substitute metal; aesthetic and quotidian material; industrial and economic product; geographic and geopolitical entity; multinational and imperialist agent. It is deleterious to the natural environment and to the human communities involved in its supply chain, as well as harmful to health, despite its use in foodstuffs and vaccines, among many other applications (Ghérardi 2016). In other words, aluminum encompasses a variety of modes of existence, each with its own temporality, which intersect and manifest in diverse ways. The ethical and ecologically responsible engagement of societies with this material depends on political, economic, and social choices, and, above all, on the establishment of a community consensus that transcends interests confined to nation-states and producing industries.

Throughout the twentieth century, aluminum and its metallic alloys became emblems of technological progress. Indeed, the existence of these materials signifies more than their mere discovery or invention: their existence becomes possible only in response to societal demands. Nevertheless, these demands are tied to an economy of promises constructed by the promoters of new materials, while the risks to health and the global environment receive scant emphasis. This enables us to advocate for diverse and long-term inquiries into the various modes of existence of aluminum. Consequently, decisions concerning this material should not be confined to its economic regulation, which is structured around promises that inspire us yet render us blind to the associated problems.

Chemistry and the Cooling Industry

The artificial production of cold represents a cultural inflection point in the preservation and transportation of food. Until that time, traditional preservation methods were used, such as drying, smoking, desiccation with common salt (salting), immersion in aqueous solutions of vinegar or brine, or natural ice. In the nineteenth century, a significant advancement in the preservation of red meat was achieved by the chemist Justus von Liebig (1803–1873), who developed a method to produce meat extract that enabled the reduction of approximately 30 kg of beef to 1 kg of extract while maintaining its nutritional properties. This method was implemented on an industrial scale by the first multinational in the food sector, LEMCO (Liebig's Extract of Meat Company Limited), established in Uruguay in 1863, which exported the extract globally. However, the artificial production of cold terminated the chemical preservation method employed by LEMCO, leading to the sale of the company in 1924, thereby concluding a cycle of innovations in the meat preservation industry. From this period onward, preservation and transportation were conducted in natura in refrigerated facilities installed on trains and ships (Lewowicz 2016).

5 This is because, in the heart of the Amazon, the Belo Monte plant is nearing completion, whose electricity generation will be primarily allocated to aluminum production (Val 2010; Pinto 2012).

Nevertheless, chemistry continues to play a crucial role in the food preservation process, as it has since then been indispensable for the production of artificial cold. The Scottish chemist William Cullen (1710–1790) was the first to produce cold artificially by connecting a vessel containing vitriolic ether (ethyl ether, $C_4H_{10}O$) to a vacuum pump, inducing the evaporation of the ether. This mechanism absorbed heat and caused the formation of a layer of ice on the outer wall of the container. The first liquefaction of a gas was achieved by the French chemist Guyton de Morveau (1737–1816). He reacted ammonium chloride (NH_4Cl) with calcium oxide (CaO), and the ammonia gas (NH_3) produced passed through a snow bath mixed with calcium chloride ($CaCl_2$), which caused the temperature to drop below -30°C, thereby obtaining liquid ammonia (Guyton 1799, 290). However, the first systematic and documented investigation of the liquefaction of various gases emerged in 1823 and was proposed by the English chemist and physicist Michael Faraday (1791–1867) at the Royal Society. Through thermal decomposition of certain salts inside a curved tube, Faraday produced temperatures capable of liquefying gases such as ammonia, sulfur dioxide (SO_2), chlorine (Cl_2), and carbon dioxide (CO_2) (Faraday 1823).

The liquefaction of gaseous substances was fundamental to the emergence of mechanized cold production, as some of them came to be used as refrigerant fluids. The most common form of refrigeration technology was initially developed by the American inventor Oliver Evans (1755–1819) and was patented by the English Jacob Perkins (1766–1849) in 1834. It is based on the principle that when a liquid is forced to evaporate, it removes a large amount of heat from its immediate surroundings, and when this vapor condenses, it releases heat. The refrigeration machine comprised five basic components: compressor, condenser, evaporator, expansion device, and refrigerant. The technology is thus based on a gas that is readily condensed by cooling or compression, with a boiling point between 0°C and –50°C. The distinction between good and poor refrigerants among substances lies in their thermodynamic properties. However, physical properties alone are insufficient for selecting a refrigerant, as chemical requirements are paramount.

A substance cannot be employed as a refrigerant unless it is chemically stable and exhibits certain characteristics, such as being non-toxic, non-corrosive, non-flammable, and non-explosive. Refrigeration relies on the repetition of thermodynamic vaporization-condensation cycles of a refrigerant. The vaporization process, i.e., the transition of a fluid from the liquid to the vapor state, cools the machine's interior by absorbing energy from its surroundings. During the inverse condensation process, the vapor reverts to the liquid state, releasing energy into the machine's external environment. Few substances have boiling points within this temperature range, and the number of such substances available during the 1920s was fewer than ten. In the early era of refrigeration, the gas most commonly employed across applications was ammonia, which, despite its toxicity, was neither flammable nor explosive and was also soluble in water. Several other gases were used on a smaller scale or studied for potential use, such as ethyl ether ($C_4H_{10}O$), methyl chloride (CH_3Cl), sulfur dioxide (SO_2), or carbon dioxide (CO_2) (Christie 2003, ch. 2).

The cooling industry developed in Europe and the United States at the beginning of the twentieth century, a period frequently identified as the "Second Industrial Revolution". This new industry utilized the infrastructure of the electrical, railway, and maritime systems, which constituted the most well-organized and extensive industrial networks. An example of the cultural inflection caused by this new industry in the preservation and consumption of food is found in the establishment of a cold chain established by France in the first decades of the century. The objective was to transport beef from Argentina and fish from the colony of Saint-Pierre-et-Miquelon, located in North America, in order to both supply the needs of the Army during the First World War and promote the consumption of frozen fish, which was scarcely appreciated by the French population. This "cold chain" opened a new horizon for refrigeration, as it consisted of a technical system that delayed the expiration date of perishable foods, thereby expanding their commercial distribution at regional, national, and international levels (Delaire and Teissier, 2020).

This cooling industry would permeate societies following the invention of the first domestic refrigerators. The first refrigerator for domestic use was called DOMELRE (an acronym for domestic electric refrigerator). Invented by the American engineer Fred Wolf Jr. (1879–1954) in 1913, the electric device held immense potential, as it enabled refrigeration without the use of ice, which was common at the time, and operated at low costs given the affordability of electricity. Mass electrification, first in Europe and the United States, and subsequently worldwide throughout the twentieth century, was crucial for the expansion of the cooling industry. Without electricity and its large-scale generation via the first hydroelectric plants, domestic refrigeration would not have been feasible. Although DOMELRE offered greater precision in cold control, domestic refrigeration still lacked reliability. In the subsequent decades, however, domestic refrigerators entered the mass market, increasing the consumption of refrigerant (Rees 2013, 137).

Nonetheless, the toxicity of ammonia and other refrigerants remained an issue. A family of substances known as chlorofluorocarbons (CFCs) had been studied since the late nineteenth century, beginning with the synthesis of its first component, dichlorodifluoromethane (CF_2Cl_2), by the Belgian chemist Frédéric Swarts (1866–1940). However, it was the American chemist Thomas Midgley Jr. (1889–1944) who first demonstrated the refrigerant properties of CF_2Cl_2, which was patented in 1929 by the DuPont company, in consortium with General Motors, under the name Freon 12 or R12. Production was carried out by the reaction between carbon tetrachloride (CCl_4) and hydrofluoric acid (HF). Other members of this family also began to be utilized, such as CFC 11 (trichlorofluorocarbon, $CFCl_3$) and CFC 113 (trichlorotrifluoroethane, $C_2F_3Cl_3$). The principal characteristics that rendered CFCs extensively used in refrigeration, as aerosol propellants, and in the expansion of foams such as polyurethane included non-flammability and non-explosiveness, chemical stability, and being non-toxic to living organisms. Additionally, they exhibited physical properties conducive to their application in a variety of contexts, such as high vapor pressure, low vapor-phase thermal conductivity, and compatibility with numerous materials (McFarland 1989). These properties of CFCs allowed for their safe use in both industrial and domestic refrigerators, as well as supporting a new product line within the refrigeration industry: residential and automotive air conditioners.

Initially, the replacement of hazardous refrigerants with CFCs appeared to be an ideal industrial solution. However, chemical products can exhibit unpredictable behaviors depending on the contexts in which they occur. While it is true that CFCs exhibit low toxicity to living organisms, their molecules have proven to be extremely destructive to the ozone layer (O_3), located in the stratosphere. Research, conducted in the 1970s by the chemists Mario Molina and Sherwood Rowland at the University of California, and published in the journal Nature, revealed the destruction of the ozone layer by CFCs. According to their findings, CFCs persist in the atmosphere for extended periods, ranging from 40 to 150 years, and the chlorine contained within the molecule is released and reacts catalytically with ozone; that is, the chlorine remains unchanged throughout the process. Each chlorine atom could destroy approximately 100,000 ozone molecules before becoming inactive (Christie 2003, ch. 5).

The work of Molina and Rowland was fundamental in alerting the world to the enormous problem posed by chemicals previously considered to be of low risk. In 1978, US health and environmental authorities prohibited the non-essential use of CFCs in aerosols, which were replaced by propane (C_3H_8) and butane (C_4H_{10}), a measure subsequently adopted by Canada and the Scandinavian countries. In 1987, 93 countries signed the Montreal Protocol, which established limits on the production of CFCs and a gradual reduction in their use, as well as requirements for their recycling. Under the auspices of this protocol and national regulations, significant reductions have been observed in the production, use, emission, and atmospheric concentration of CFCs, with clear evidence of the recovery of the stratospheric ozone layer. Undoubtedly, without the early warning issued in 1974 and the Montreal Protocol of 1987, the destruction of the ozone layer would likely be far greater than what is observed today (Velders 2007).

Brazil is a signatory to this Protocol (Decree No. 99.280/90), and by decision of the National Environmental Council in September 2000 (Decree No. 99.220), the use and production of CFCs and other substances harmful to the ozone layer were prohibited (IBAMA, 2024). These preventive measures prompted chemists to seek alternatives to meet the needs of the refrigeration industry. Currently, the primary alternative used as a refrigerant in the most common appliances is tetrafluoroethane ($C_2H_2F_4$), a molecule derived from the original family of CFCs and, although not entirely harmless, substantially reduces harm to the ozone layer. In September 2025, a report by the World Meteorological Organization (WMO), a UN specialized agency, indicated a significant, at least on statistical grounds, likelihood that the ozone layer will recover by the 2050s.[6]

The case of CFCs exemplifies how chemistry can offer solutions to industrial and social demands while simultaneously generating major environmental problems. It also reveals the unpredictability inherent in chemical molecules, which may be harmless in certain contexts yet highly destructive in others. Therefore, it is imperative to regard this unpredictability as an integral criterion in justifying the production, use, and disposal of molecules synthesized by chemists and made available by industry to society. It is necessary to consider new relationships with other substances, the environment, and human and animal life. Accordingly, chemical research should not be confined to the laboratory but rather encompass the lifeworld, understood as the interrelations among different substances and materials and elements of the social, cultural, and environmental world.

Unpredictability serves as a cautionary principle even with respect to chemical molecules developed under the paradigm of sustainable development. Undoubtedly, in the 1930s, CFCs were considered an advancement, although they later revealed themselves to be the antithesis of the sought-after sustainability. This case also points us to a fundamental scientific and social stance of precaution regarding possible harms not yet documented, highlighting the need for continuous scientific research that is not exclusively centered on the anthropocentric potential use of a substance. It was the scholarly investigations of Molina and Rowland that prompted the protective measures adopted in international conventions aimed at safeguarding the ozone layer. Hence, a necessity for continuous funding of independent academic research, particularly by public authorities. Ultimately, this case also reveals the significance of chemistry in producing one of the principal commodities demanded by contemporary societies: refrigeration. If the mastery of fire dates back to prehistory, the control of cold is a product of modern science, of which chemistry is an integral part.

Amphetamines and the Era of *Smart Drugs*

Another study that vividly illustrates the situated and relational character of chemical substances is that of amphetamines, a class of psychotropic substances (psyche/mind – topos/alteration) belonging to the amine functional group, which were developed to mimic the function of adrenaline, a natural defense mechanism of our organism. Its structure derives from ephedrine, an ancient Chinese medication extracted from the genus Ephedra, used by many cultures as a nasal decongestant, an asthma treatment, and a stimulant. Nagai

6 https://wmo.int/news/media-centre/wmo-bulletin-show-successful-recovery-of-ozone-layer-driven-science Accessed on 09/20/2025.

Nagayoshi, a Japanese chemist and pharmacologist, first isolated methamphetamine from ephedrine in 1885, and two years later, amphetamine was synthesized in Germany by the chemist Lazar Edeleanu. Amphetamine acts directly on the central nervous system, acting on dopaminergic, noradrenergic, and serotonin transporters. Over years of research, numerous substitutions in the chemical structure of amphetamines have been carried out, yielding other pharmaceuticals with varied properties and applications.[7]

It is important to highlight that the trajectory of these molecules cannot be explained solely by theoretical or experimental motivations: they are entangled with economic, military, and social interests. Thus, drugs do not preexist their uses: they are manufactured, socialized, and resignified within specific historical and cultural contexts. As Joseph Dumit demonstrates in "Drugs for Life" (2012), this is not merely a matter of chemical substances in circulation, but of the constitution of a way of life mediated by chemistry, in which health becomes an object of ongoing management. Dumit refers to different "biomedical modes of living", among them "living better through chemistry", whereby medications cease to be punctual interventions against symptoms and instead become part of a lifestyle. From this perspective, pharmaceuticals not only treat diseases but also reconfigure the boundary between health and pathology, as well as risk and prevention. What is at stake is a genuine "chemical mode of addressing medicalization", and this shift reveals that drugs do not possess a neutral existence but are asserted as historical and relational entities whose meanings are socially produced and contested (Zorzanelli 2013).

Indeed, following its synthesis by Lazar Edeleanu in 1887, amphetamine reached the market decades later, in 1932, when it began to be sold as an inhaler for the relief of nasal congestion under the brand Benzedrine. The substance's potential, however, was revealed even more extensively during the Second World War, when it was distributed to soldiers to reduce fatigue, prolong wakefulness, and enhance physical endurance. Shortly thereafter, in 1937, Benzedrine was also made available in tablet form, achieving extraordinary sales—over 50 million units in the first three years. In the 1950s, the drug expanded its therapeutic scope and became frequently prescribed in the United States for the treatment of narcolepsy, alcoholism, and depression (Muakad, 2013). In subsequent years, new uses were established: use among truck drivers, attracted by its stimulant properties, and the discovery that certain amphetamine derivatives functioned as appetite suppressants. These "weight-loss agents" quickly gained popularity, being produced both by pharmaceutical companies and compounding pharmacies (Muakad 2013).

Methylphenidate ($C_{14}H_{19}NO_2$) – an amphetamine derivative synthesized by Leandro Panizzon and patented in 1954 – is a central nervous system (CNS) stimulant widely commercialized in formulations known as Ritalin and Concerta. Initially employed to reduce motor restlessness and enhance attention and memory, it now holds a central position in the treatment of Attention Deficit Hyperactivity Disorder (ADHD), with frequent prescriptions in educational settings. (BPR, 2010). According to the UN (2019), global manufacturing of methylphenidate increased between 2008 and 2017, as production in 2008 was approximately 1.5 million defined daily doses for statistical purposes (S-DDD), whereas in 2017 the figure reached approximately 2.4 million S-DDD produced. According to the 2011 Report of the International Narcotics Control Board, from the United Nations (UN), methylphenidate is the most widely consumed stimulant in the world, and its use requires special regulation due to its potential for abuse and dependence (Nasário and Matos 2022). In Brazil, it was approved in 1998 for the treatment of ADHD in children aged six and older, as well as for the

7 The chemical formula of amphetamine is $C_9H_{13}N$, and its base is typically a colorless, volatile oil insoluble in water. The most common salt is the sulfate, a whitish powder soluble in water, representing the form of most illicit formulations; it can also be found as tablets (EMCDDA, 2015). Amphetamines exist as two optically active isomers: dextro and levo. They are typically consumed either as d-amphetamine or as a racemic mixture (Juaristi and Stefani 2012).

treatment of narcolepsy in adults—a disorder characterized by excessive daytime sleepiness and affecting 0.2 to 0.5% of the global population.

If amphetamines in the early twentieth century were employed for respiratory problems, narcolepsy, and fatigue, these psychotropic substances have since become remarkably widespread, now exhibiting non-therapeutic and frequently illegal use. In other words, today, thousands of healthy individuals consume these drugs recreationally. Here, another mode of existence of these substances emerges: their use for cognitive enhancement. After all, enhancing everyone's productivity is a "duty" of our society characterized by the era of full positivity (Han 2022). Indeed, the pursuit of positivity and full social recognition has become a powerful impetus for purely recreational and instrumental pharmacological use. We observe that the consumption of these amphetamines and their derivatives by healthy individuals is reaching increasingly alarming levels, as they have the capacity to intensify attention, improve cognition, enhance physical performance, optimize memory and concentration, extend wakefulness, and ultimately elevate overall productive capacity. Internationally, in high-income countries, consumption rates of medications for ADHD reach approximately 6.39 DDD/TID, whereas in low-income countries they remain around 0.37 DDD/TID, indicating disparities in access and therapeutic use (Chan 2023).

Beyond mere statistics of expansion, these data indicate a bioeconomic phenomenon: methylphenidate circulates between therapeutic regimes and performance logics, traversing boundaries between health, education, and social demands. Whereas in the past non-therapeutic drug use served to facilitate the trance between the profane and the sacred realms, bearing a more spiritual significance, today such use is directly associated with increasing human efficiency and productivity. This denotes a relationship between the use of amphetamines and their derivatives and institutional domains such as health, education, labor, and economy.

Whitehead, in problematizing the method of invention, argues that material objects, such as molecules, exist within a material and informational environment. Indeed, the chemical and pharmaceutical industries do not produce molecules isolated from their context. An environment of informational and material entities permeates the constitution of a given entity (Whitehead 1985). This is why molecules are improved and enriched through laboratory practice; however, information such as the potency, metabolism, and toxicity of drugs, for example, is fundamental to the invention of these newly informed materials. In this regard, chemistry should be understood primarily as a science of relations or associations, and thus a given molecule or substance should be conceived not only as a physical or chemical entity but, above all, as a historical entity (Whitehead 1978). Moreover, we now add, a cultural one. The properties of a water molecule differ at temperatures above and below 0°C, the properties of a hydrogen atom bonded to a water molecule differ from those of a hydrogen atom bonded to a chlorine molecule, and the properties of a substance vary considerably depending on whether it contains impurities. We must engage with real entities embedded in specific contexts. The challenge posed, as Latour already cautioned, is to multiply the possible relations among the different modes of existence of a molecule both inside and outside the laboratory, so as to achieve increasingly satisfactory outcomes (Latour 1999; Barry 2001).

If this is the case, we must ultimately emphasize the consequences of this new "measured" and informational mode of chemical research. To date, "smart drugs" have been approved solely for specific conditions, such as narcolepsy and ADHD, at specified dosages. There are significant concerns regarding the impacts of these pharmaceuticals when consumed by healthy individuals, particularly in excessive doses. As these drugs modulate key neurotransmitter systems such as dopamine and norepinephrine, users assume significant risks associated with unregulated use. We recognize that the risks are a fundamental concern in the mass recreational consumption of amphetamines, which can induce addiction, anxiety, pronounced cardiovascular side effects, tachycardia, and arrhythmia; when ingested in high doses, they can also elicit neurotoxic effects, resulting in irreversible damage to dopaminergic or serotonergic neurons in the brain; peripheral hyperthermia through activation of the adrenal system, as well as the onset of stereotyped behavioral effects (Silva 2002). All these factors may or may not manifest, depending on the dose, the environment, the interactions with other drugs, and the individual's body.

As Nikolas Rose illustrates in *The Politics of Life Itself* (2013), human life in the twenty-first century has become regulated by increasingly refined biomedical interventions operating at molecular and neurochemical levels. In this context, we deal not only with chemical substances that circulate socially but also with the constitution of a genuine "neurochemical ethos" that reconfigures the very experience of subjectivity: to be healthy and productive increasingly entails being chemically calibrated to meet the demands of performance and social recognition.

Through this analysis of the diffusion of amphetamines and their derivatives, we observe that the use of a drug may expand depending on its mode of socialization within cultural frameworks and its use at the individual level, taking into account the interactions between the individual and society. The effects of a drug due to abuse are intrinsically linked to the images and perceptions socially constructed around the chemical substance. Contemporary society accepts illness but does not tolerate suffering and anguish. Low productivity, drowsiness, boredom, anguish, slowness, sadness, or disappointment should not always be medicated or avoided at all costs, for they are, ultimately, constitutive aspects of the human experience.

Conclusion

Chemical entities may exhibit various modes of existence. In the case studies presented here, we take as a starting point a relational epistemic perspective on materials. Thus, we emphasize that chemical entities exist in diverse modes and intertwined temporalities: promises that direct investments and imaginaries (aluminum), indeterminacies that give rise to unforeseen effects (CFCs in the cold chain), and artificial forms of life in which psychotropic molecules come to modulate routines, performances, and social expectations (amphetamines). In all cases, chemistry appears not as a catalog of fixed and predetermined essentials, but as a practice that produces existences, that is, novelties and, consequently, zones of the unknown.

In the case of aluminum, the "economies of promises" illuminate how the social existence of a material is cofabricated by technological marketing, financing regimes, and industrial policies, shifting the focus from "what it is" to "what it may come to be" and "at what cost." Such an approach invites narratives of "material biographies" – following extraction, processing, use, and disposal – as analytical and governance instruments. The cooling industry, in turn, makes unpredictability explicit: molecules once celebrated for their low local toxicity became, decades later, global agents of ozone depletion. Institutional learning – from the earliest scientific evidence to multilateral responses – currently underpins projections for the recovery of the ozone layer, a success attributable to science and regulatory coordination. This case offers a model for chemical policies that integrate long-term surveillance, periodic review, and prudent technological substitutions. Amphetamines, in turn, demonstrate how substances migrate from therapeutic niches to everyday performance regimes, inscribing themselves within sociotechnical imaginaries of productivity and optimization. Considering these displacements necessitates problematizing what it truly means to "live better through chemistry".

In sum, clarifying these three conceptual operators – economic promises, unpredictability, and artificial positivity – indicates significant societal decisions. For example, that of a "situated precaution," namely, incorporating the precautionary principle into decisions regarding the synthesis and substitution of molecules, while acknowledging scale-related uncertainties and irreversibilities. This requires gradual regulatory triggers, environmental monitoring, and data transparency. That of responsible innovation: adopting frameworks for anticipation, reflexivity, inclusion, and responsiveness in chemical research and industry—projecting scenarios, revealing the values at stake, including affected parties, and responding to new evidence (as demonstrated by the lessons from CFCs) (Stilgoe 2013). Moreover, of biographies and metrics: institutionalizing assessments that track complete "material lives" (from the mine to the organism and the ecosystem), incorporating metrics of exposure, persistence, bioaccumulation, sociotechnical lock-ins, and reversal costs. It is the convergence of these elements that constitutes the "material biographies", which function simultaneously as a historiographical method and as a tool for scientific and industrial policy (Bensaude-Vincent 2022). Reflecting on chemistry through these three conceptual operators thus reinforces the necessity of considering chemical entities through the lens of their relational ecologies.

We consider the promotion of conceptual clarification as an important task for the philosophy of chemistry. Indeed, by articulating the laboratory, industry, and the lifeworld, it provides fundamental concepts to rethink experimental practices (which must be attentive to the generation of new substances and the risks of indeterminacies), public policies (which should integrate precaution and responsible innovation), and collective narratives (which should stay alert to the promises that drive us).

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