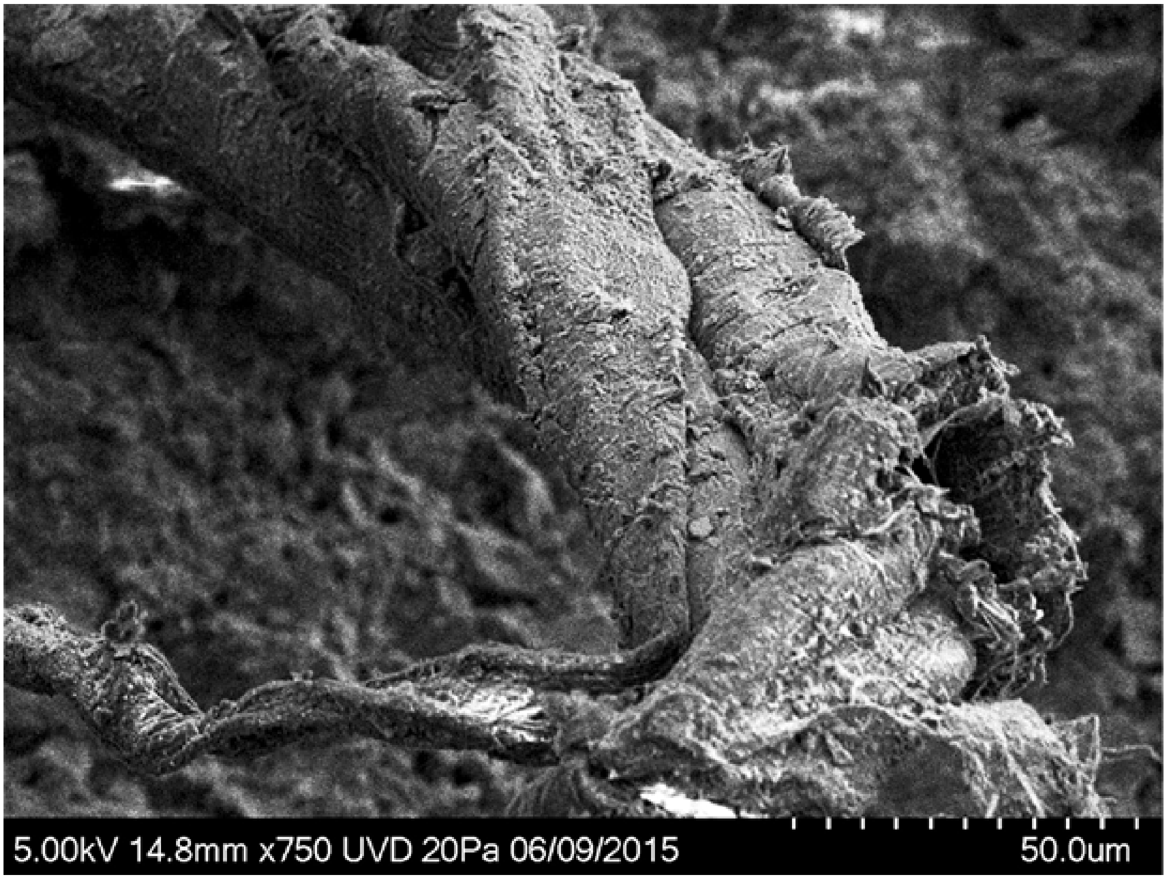
1

Arachne's Web

Then, going off, she sprinkled her with juice,
Which leaves of baneful aconite produce.
Touch'd with the pois'nous drug, her flowing hair
Fell to the ground, and left her temples bare;
Her usual features vanish'd from their place,
Her body lessen'd all, but most her face.
Her slender fingers, hanging on each side
With many joynts, the use of legs supply'd:
A spider's bag the rest, from which she gives
A thread, and still by constant weaving lives.

OVID, *METAMORPHOSES*

The Missing Majority



Scanning electron microscope image from the Museum National d'Histoire Naturelle in Paris, showing multiple fibres in a Palaeolithic cord fragment. From Bruce Hardy et al., 'Direct Evidence of Neanderthal Fibre Technology and its Cognitive and Behavioral Implications'.

When we think about the history of technology, weaving is probably not among the first things that come to mind. And yet weaving has had an incalculable impact upon human civilisation: from the production of clothing to the birth of modern programming, this technology has accompanied human history as a silent presence, intertwined with the life of every one of us. The oldest traces of woven fibres among *homo sapiens* are known to date back more than twenty thousand years, to a time well before the birth of agriculture, but it is probable that our species was not the only one to have developed the technique of weaving: a recent study has revealed the discovery of a woven fragment attributed to Neanderthal man, which would take weaving back as far as ninety thousand years.[1]

Elizabeth Wayland Barber, an archaeologist and expert in the history of weaving, argues that widespread ignorance of this fundamental aspect of the history of technology owes largely to the perishability of fabric fibres, physical traces of which are easily lost with the passage of millennia.[2] This then is also the reason why, when we imagine technologies of the past, we think of hard materials such as stone and metal, while fabric, by its nature soft and organic, ends up being almost completely forgotten.

It is most likely that the 'Stone Age' was not really the Stone Age, and that most of the technologies used by prehistoric humans were characterised by the use of organic materials that have been almost completely lost. These perishable technologies that were certainly a part of human life since the Palaeolithic, but of which only a few traces remain, have been dubbed by the archaeologist Linda Hurcombe *the missing majority*.[3] Hurcombe argues that this missing technological knowledge is not just a problem of the incompleteness of the archaeological record, but has also had an incalculable influence upon our vision of past societies. The selective forgetting of the past, so evident in the case of perishable materials used in antiquity, has much to teach us about the way we think about the technologies of the present and imagine the technologies of the future. Because the materials we use are not passive objects but, on the contrary, are determined by our socio-cultural life and in turn determine our relationship with the world, forming what is called *material culture*: a culture that is shaped by the invention, production, and use of the materials around us. In other words, a culture cannot be separated from the materials that characterise it; when a substantial portion of them is forgotten, our knowledge of that culture suffers enormously.

We must always keep in mind that the materials we use on a daily basis say a lot about our culture, and that our cultural perspective is a determining factor in the choice of materials with which we build our world. When we look at a fabric, we usually don't see it as a technological object, because its flexibility and softness do not fit our mechanistic image of technology based on rigid, hard materials that can survive for tens of thousands of years; yet in terms of complexity and adaptability, fabric is a far more advanced material than a piece of metal. The same prejudice that has influenced our perception of prehistoric technologies as nothing but a collection of sharp stones—and has made us neglect fine weaving, food preservation, and pigment preparation—also comes into play when we imagine a future based on steel and silicon. It is possible, indeed it is certain, that we will have to learn to make our technologies softer and more flexible if we are to have any chance of overcoming the challenges that lie ahead. At a time when we are obliged to reflect upon our impact on the planet, an impact so great that it has become geological, our best technologies will be those that leave no trace.

Perhaps another reason why we so rarely consider weaving is that it is an essentially feminine technology. A very common prejudice would have it that the techniques women have developed and kept alive since the dawn of our civilisations are not real technologies; instead they are treated almost as inexhaustible and mysterious natural resources: they are seen as the result of innate tendencies, their existence is taken for granted and, too often, their complexity is underestimated. The Jacquard loom, designed in 1801 by Jean-Marie Jacquard, is widely regarded as the first programmable machine ever designed, and used a system based on perforated cards surprisingly similar to those used more than a century later in the first computers. It was the Jacquard loom that inspired the mathematics of Ada Lovelace, who, together with Charles Babbage, developed the project for a computational machine called the *Analytical Engine,* in principle capable of performing any algebraic work. As is often the case with new technologies, the Jacquard loom also met with a great deal of resistance from public opinion. In a warning against its widespread adoption, the poet Lord Byron described weaving with the Jacquard machine as *spider-work*. Most likely Byron had never looked at a spider's web closely enough: if he had, he would have appreciated its extraordinary complexity, and perhaps would have learned to appreciate the loom's ingenuity too.

This digression on the most ancient art of weaving in a book dedicated to contemporary materials science may seem perplexing. It could be argued that materials science, unlike weaving, is a very recent technology, born and raised in the clinical white laboratories of the twentieth century and certainly not in the tepid half-light of a palaeolithic cave. What I find most striking about fabric, however, is not so different from what fascinates me when I look closely at a new material. At the basis of weaving and of modern materials science alike there lies the idea, as simple as it is revolutionary, that the repetition of many small identical elements—the 'threads' of the loom—can produce a new object with remarkable properties not possessed by the individual starting elements alone. The transition from a simple tangled ball of yarn to a complex fabric is determined by *structure*: as every expert weaver knows well, weaving is not just any old way to hold threads together, but a set of specific methods which produce particular properties unique to each fabric, making it more elastic, more resistant, warmer, or more breathable. Many advanced materials today are designed and constructed in exactly the same way, trying to capture the exact convergence of material and structure—'thread' and 'weave'—capable of endowing the material with the desired properties. The fact that the loom was the model for modern computational machines highlights a fundamental feature of complex matter, namely that its structure can store a certain amount of information which is not imparted from the outside, like words inscribed onto a piece of paper, but is 'written' in the relationships between the microscopic elements that make it up. In other words, as in the case of fabric, the strength of our most innovative materials lies in their *cooperative* and *relational* nature, which is expressed in a diffuse and decentralised structure endowing the material with properties that its individual parts do not possess. The result is an object that is both adaptable and resistant, because its integrity depends not on the preservation of a few elements, but on the synergy of all the fibres that make it up.

Just as our vision of the communities of the past is influenced by our knowledge of the materials they used, if we are to imagine a different future then our ideas about technology will have to change accordingly. In my view, it is not a question of accepting or rejecting technology en bloc; those who raise the question in these terms overlook the fact that technologies are plural, and that there are infinitely many ways to relate to the materials around us better than we have traditionally done. We should always believe that a different future is possible, even if this requires us to revolutionise our perspective on how our technologies act in the world. And this means first of all rethinking the materials with which we build our lives so that they are increasingly *intelligent*, i.e. flexible and able to enter into dialogue with their environment. The idea that a material can be intelligent might appear counterintuitive; intelligence is a category we like to apply very sparingly—not least, perhaps, because it makes us feel special. But in fact, although they may be quite distinct and different from any living material, non-living materials can be far more dynamic and complex than you might imagine. After all, life itself, before coming alive, was nothing but chemistry; if there is any continuity in nature, then we must admit the possibility, if only in principle, that chemistry can produce systems of incredible intelligence and complexity.

---

1. B.L. Hardy et al., 'Direct Evidence of Neanderthal Fibre Technology and Its Cognitive and Behavioral Implications', *Scientific Reports* 10 (2020), 4889.
2. E. Wayland Barber, *Women's Work, The First 20,000 Years: Women, Cloth, and Society in Early Times* (New York: Norton, 1995).
3. L.M. Hurcombe, *Perishable Material Culture in Prehistory: Investigating the Missing Majority* (London: Routledge, 2014).

A Spider’s Work

Arachne's contest with Minerva, as depicted in the fifteenth-century manuscript *Ovide moralisée*.
Image: Warburg Institute.

In the West, myths that tell of the relationship between man, or woman, and technology are often rather tormented: from the torture of Prometheus to the fall of Icarus, Greek mythology is full of warnings against the dangers of using technology to go beyond human limits, even when this is done out of necessity or for the well-being of the community. Our contemporary sensibilities, however, are often more sympathetic to the reckless figures of these myths, who appear to us as heroes and heroines in revolt against an unjust divine arrogance. Perhaps Ovid already felt this sympathy when, in the sixth book of the Metamorphoses, he tells the story of Arachne, a woman of humble origins but endowed with a superlative talent for weaving. According to the myth, Arachne refuses to attribute her talent to a divine gift, believing that it is exclusively the product of her own ingenuity. The goddess Athena, the patron of weaving, angered by Arachne's pride, presents herself to Arachne in the form of an old woman, recommending that she implore the goddess's forgiveness without delay. When Arachne refuses, Athena reveals herself and challenges the defiant weaver to a contest. While Athena weaves a tapestry depicting the great deeds of the Olympian gods, Arachne, with equal mastery, weaves one showing the deceptions and violence suffered by women at the hands of the gods.

At this point, an enraged Athena destroys Arachne's blasphemous tapestry and attacks her, until she is forced to commit suicide. Only at that point does Athena, merciless to the last, decide to save Arachne's life but, as punishment for her presumption, forces her to spend the rest of her days weaving her web in the body of a spider.

The myth of Arachne raises an interesting question: Do our technologies belong to us, and can we therefore use them to change what seems wrong and unjust in nature, or are they divine forces which, like the fire of Prometheus, we may borrow but must always handle with sacred reverence? Too often it is suggested that technological progress is a destiny already written, but in reality there is very little that is deterministic in the development of the technologies we use. The path that leads to the emergence of a new technology is far from linear, and a critical view of this process is crucial to understanding technology not as a Pandora's box we have found ourselves holding, but as a canvas in which we weave one thread at a time, and where our personal and cultural perspectives carry a great deal of weight. The metamorphosis of Arachne only makes explicit an already implicit truth: that the tapestry is inseparable from its weaver, and that technology is inextricably woven into the life of the one who constructs it.

Like weaving, the design of new materials was born in response to the practical needs of human life. This leads us to underestimate its scope, based on the assumption that an innovation that solves a practical problem cannot be worthy of theoretical consideration. For we too are convinced that the design of new materials, like weaving, is little more than ‘spider’s work’: a boring and repetitive technical procedure that has very little to teach us about ourselves or the world. We thus become entangled in a strange paradox: a great deal of scientific knowledge about phenomena that are manifest only on a cosmic or subatomic scale, in times and spaces so vast or so tiny that they are intuitively elusive to our mind, end up being much better known than the principles of the applied sciences with which we build our everyday technologies. Think, for example, of the theories of relativity and quantum theory, which are undeniably fascinating and have deep epistemological implications, but which have long monopolised public discourse on science without leaving much room for anything else. It is quite likely that the average woman or man in the street will have a better grasp of the riddle of Schrödinger’s cat than of the chemical structure of the polyester their socks are made from.

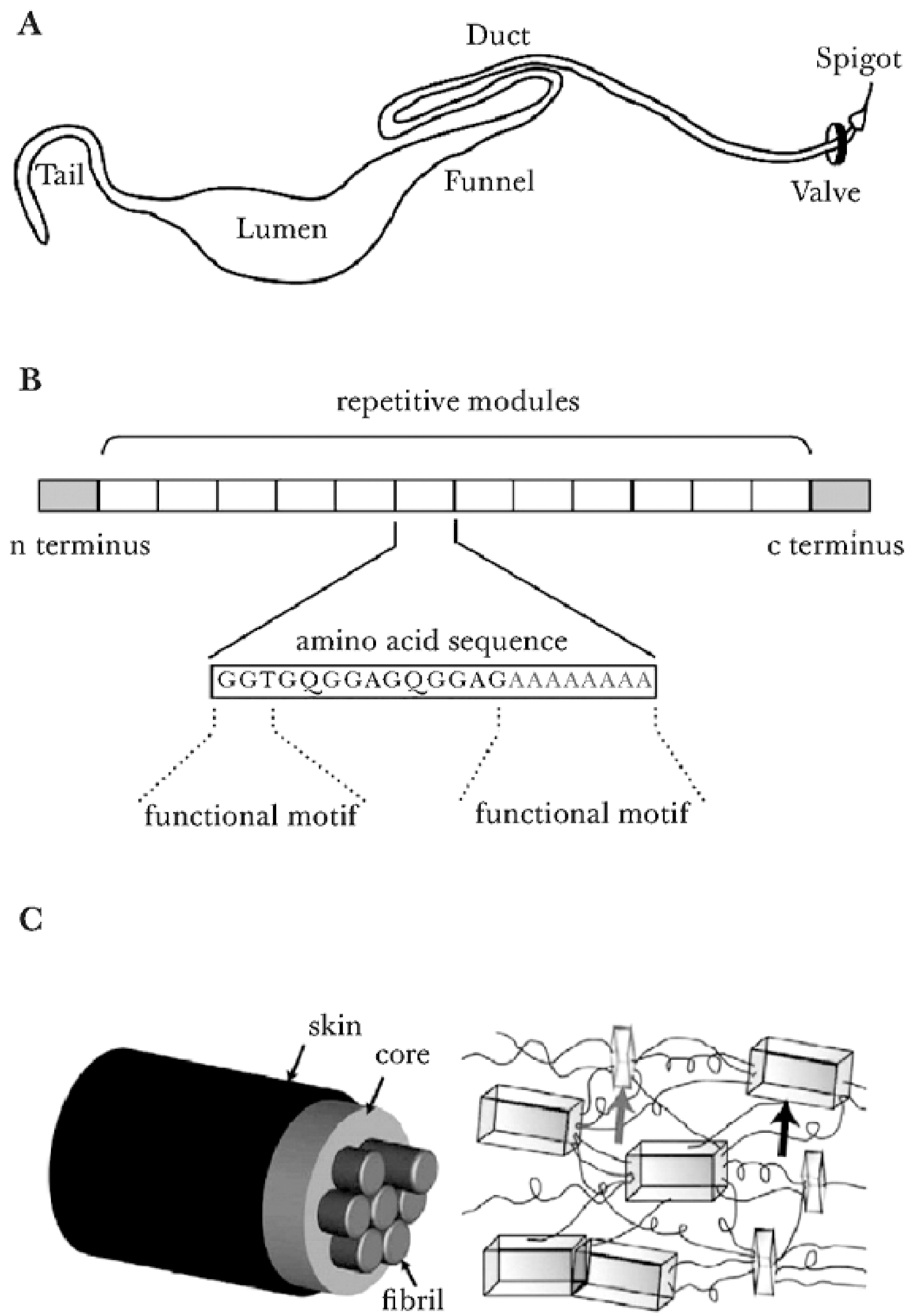
This reminds me of the famous story of Thales, the ancient philosopher who, too engrossed in looking up at the stars, his face raised to the heavens, ended up falling down a well. But our well is particularly deep and dark, because if we do not find a way to act radically on our material culture, the effects, as we all know, will be irreversible. Of course, that does not mean we should stop paying attention to the more theoretical sciences, nor that we must try to make sure everyone has an encyclopaedic knowledge of every material they come into contact with. On the contrary, it means acknowledging that the ability of a science to act effectively on the world does not imply its irrelevance, but should instead prompt us to look at it more closely, because it offers us the opportunity to grasp the thread that runs back and forth between our ideas and the material world in which they are immersed. Moreover, in the face of global ecological crisis, we can no longer allow ourselves to leave unquestioned those disciplines which, well before all others, will have a direct impact upon the destiny of our species (and countless others): the applied sciences, to which we entrust the incredibly complex task of building our future. The fabric that binds Arachne to her own destiny is the same that binds ours indissolubly to the materials we choose to construct.

The divine wrath Arachne calls down on herself is perhaps linked to the fact that she is the repository of precious knowledge. It is not just her tapestry—all the infinite variety of materials that exist in nature are woven together into a kind of fabric: a multiform molecular warp that expresses the dynamic complexity of life itself. Is it possible for skilled weavers to artificially reproduce this complexity? Is it possible to imitate it or even supercede it with an artificial material? Perhaps it is no coincidence that one of the exemplary models of smart materials in nature is spider silk. The amazing properties of spider's webs, such as the ability of a very fine thread structure to support a much heavier animal and effectively trap very fast prey, were probably well known even in ancient times. And indeed the mythologies of many different civilizations contain references to spiders and their webs, often in the form of female figures associated with the art of weaving, like our Arachne. Clearly, the way in which a spider produces its own web, as well as the nature of the threads it uses to make it, are very different from those of a human weaver; and yet the incredible characteristics of spider silk are also largely determined by a kind of weaving, albeit one far more complex and finer than that of any known fabric.

It is important not only to know that spiders produce silk, but also that the spider is the only animal that can secrete and use it at every stage of its development, and is undoubtedly the animal that uses it to produce the most refined and complex structures. Furthermore, there is not just one type of spider silk: the composition of silks varies enormously from species to species, and the same spider will use between three and seven different types of silk, each produced in a particular gland in its abdomen. Moreover, although all spiders produce silk, not all of them use it for the same purposes. The vertical spider web that we immediately associate with the spider was certainly a later adaptation; the early ancestors of the spiders who colonised the emerging landmasses around four hundred million years ago used silk to protect their eggs and to reinforce their underground shelters. Even today there are still many species of spider that do not build the unmistakable spiral web familiar to us all; these are the sole province of the *Araneidae* family, which probably began to weave its vertical webs 'only' two hundred million years ago. In any case, the evolutionary pathway of spiders has been quite heavily determined by small molecular changes in their silk, which have allowed them to build increasingly functional and complex structures, ensuring their continuing success in a great many different environments.[1]

The reason why the spider's web has attracted so much attention undoubtedly lies in what we might generically define as its mechanical properties: it is a commonplace to compare the spider web's incredible strength to materials more commonly associated with mechanical strength, such as steel. One of the most popular and extravagant examples often put forward is the hypothetical ability of a silk thread as thick as a pencil to stop a fully-laden Boeing 747 in mid-flight. Actually, as intuitive as the concept of strength seems to us, this type of example only goes to show that defining the ability of a material to withstand a force is far from being a simple matter. There are rigid materials that are capable of deformation, but which, precisely because of their rigidity, are unable to withstand too much strain. There are pliable materials that can undergo enormous deformation without breaking, but which would be totally unsuitable for many structural applications: no engineer would dream of building a rubber bridge. To further complicate things, many materials behave differently depending on the situation: the properties of a material can change drastically depending on the size or speed of the deformation they undergo. Another fundamental aspect of material behaviour is elasticity, which has to do with a material's ability to handle the energy it receives: an elastic material hit by a moving object is temporarily deformed, but then returns all of its kinetic energy to the bullet as it regains its original form. A material with low elasticity, on the other hand, is able to absorb and dissipate at least some of the energy it receives. In the light of these complex behaviours, the comparison of a spider web with steel—or of any material with any other—tells us little, because it does not consider their respective functions. Instead, we should understand that no material is intrinsically better or worse than another, but that each material holds a specific potential hidden within its intimate chemical structure. This is a concept with which spiders are very familiar, since they have developed a wide variety of materials with very different properties depending on their use.

The type of silk that has been the focus of most interest is 'major ampullate silk', which spiders use as the main structural element in the construction of their vertical webs. This silk is the one with the most outstanding mechanical characteristics, and toward which the greatest research efforts have been directed. The threads of major ampullate silk are considerably more resistant to tensile stress, i.e. can withstand much greater forces, than any other biomaterial: their resistance is comparable to that of high-tensile steel, although it is still lower than that of advanced synthetic materials such as Kevlar or carbon fibre. But what really makes this silk amazing is its *toughness*, which can be defined as the amount of energy a material can absorb before fracturing. Since silk is considerably more extensible than steel but with a similar tensile strength, it has a far higher toughness than almost any other known material. Another type of silk produced by spiders well known for its tenacity and resistance is the viscose silk they use to construct the spiral trap at the centre of their webs: this is a silk whose specific function is to catch insects that collide with it at great speed, absorbing their energy without breaking.[2]



Production of ampullate silk. (A) Schematic drawing of the spider's silk glands. (B) Chemical structure of spider silk proteins, showing the repetitive amino-acid sequences. (C) Cross-section of a spider silk thread (left) and microscopic morphology of spider silk (right), showing the hierarchical structure of the material, composed of rigid and flexible components. From Lukas Eisoldt et al., 'Decoding the Secrets of Spider Silk'.

Confronted with such characteristics, it is easy to forget that spider silk is not an innovative material designed in the laboratory, but one that has been produced for at least two hundred million years inside the belly of an organism that we usually think of as being 'low' on the evolutionary scale. What verges on the miraculous is that this material is an almost instantaneous preparation, whereas most of the synthetic fibres we use today require high temperatures, lengthy industrial processes, and polluting organic solvents for their production. But of all the incredible characteristics of spider silk, the most important is its ability to respond to stimuli in an intelligent way, adapting its behaviour and characteristics according to the environmental conditions in which it finds itself. Silk transforms from liquid to solid in a very short time, and only does so at the exact moment it is emitted from the spider's abdomen. Moreover, the mechanical response of the web changes considerably depending on the speed of the stimulus to which it is subjected, so that if the spider freefalls into it, or if an insect crashes into its threads, its resistance and toughness increase dramatically—as if, somehow, the material *knew* of the risk of an imminent fracture. This is owing to the fact that spider silk is subject to a phenomenon known as *hysteresis*, a behaviour shared by many complex systems, from materials to electronic circuits, from neurons to economic systems. Hysteresis is, in short, a memory effect: it refers to the ability of a system to undergo irreversible change when an abrupt transformation occurs, and it is one of the ways in which material structures can adapt and retain a trace of their history. When a silk thread is stretched quickly by a moving load its internal structure is reorganised so that, when the load is removed, returning to the original state yields much less energy. This energy dissipation is essentially a form of adaptation that allows the spider web to deal with abrupt environmental stimuli that would otherwise destroy it completely. On a more general level, hysteresis could be understood as one of the concepts that define our idea of what intelligence truly is. While the response of a simple mechanical system is regulated by static input-output relationships, intelligent systems do not simply yield different effects when exposed to different causes. Arguably, what defines intelligent behaviour is the capacity of a system to retain the memory of past stimuli by transmuting it into structural change.

1. See E. Pennisi, ‘Untangling Spider Biology’, *Science* 358:6361 (2017), 288–91: 289.
2. J.M. Gosline et al., ‘The Mechanical Design of Spider Silks: From Fibroin Sequence to Mechanical Function’, *Journal of Experimental Biology* 202 (1999), 3295–3303.

Structure and Function

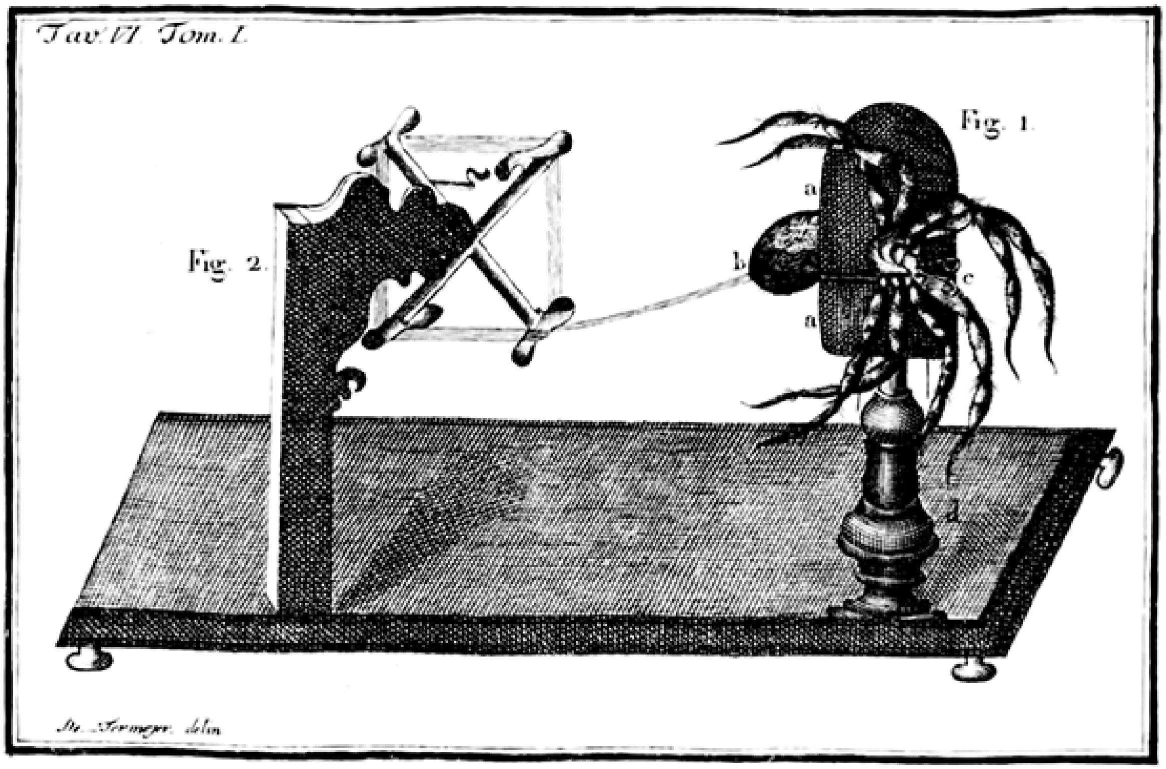
To understand the origin of these complex behaviours, we must take a closer look at the molecular structure of silk. First of all, silk is a protein, i.e. a chain—in chemistry we call it a *polymer*—of small molecular fragments called *amino acids*. In particular, major ampullate silk is obtained from a mixture of two different types of protein, which emerged at two successive moments in the spider's evolutionary history. Amino acids, the molecular units that make up proteins, are very similar to one another: every amino acid has two ends, each capable of chemically bonding with the opposite end of another amino acid, as if they were Lego bricks or puzzle pieces. Each amino acid, however, is characterised by a molecular 'pendant group' different from the others, and which gives it particular properties: in living systems there are twenty in all, which together form a sort of alphabet of life. Combining these twenty fragments yields a surprising variety of proteins, each capable of performing its own specific function, from communication between the cells of an organism to the catalysis of metabolic reactions, to specific structural functions as in the case of spider silk.

The reason why proteins are so good at doing what they do is that they have been subject to selection over millions of years of evolution. We know that amino acid sequences of proteins are encoded within genes in DNA molecules, and that evolution by natural selection acts by 'rewarding' genes that provide the best chance of survival in a given environment. In science, however, there are many different ways to interpret and answer the question *why*, and the *biological why*—the one that responds to the problem of the functioning of proteins by referring back to their evolutionary process of selection—is different from the *chemical why*. Chemistry is by its very nature a synthetic science, in the sense that, since its earliest historical origins, it has always asked how to *produce* new substances in the laboratory: for this reason, the *chemical why* is always an operational why—more like 'How is it done?' As far as proteins are concerned, what is chemically fascinating is the way in which a set of extremely simple molecular components, amino acids, can be combined to build a variety of complex objects capable of performing the most diverse functions. The *why*, in this sense, is hidden within their structure: every amino acid is capable of interacting with all the other amino acids in the same chain via its own specific side chain. The individual interactions of each amino acid are relatively simple, but when tens or hundreds of them are joined together, the interactions become incredibly complex, giving rise to specific functional structures, as when threads are woven together into fabric. This modularity, with many small simple elements interacting with one another to form complex objects, is incredibly efficient and versatile, and is something that the art of weaving and the chemistry of living organisms have in common.

The molecular fabric of major ampullate spider silk has been extensively studied, revealing a number of fascinating features. Despite the structural variability of silk from species to species, all silk proteins are characterised by the presence of two different types of amino acid sequences: some sections of the protein tend to organise themselves into rigid and strongly ordered crystalline structures, while others tend to maintain a more disorderly structure in which molecules have great freedom of movement. This alternation between rigid fragments and flexible chains is what ensures that the silk proteins will have both extremely high tensile strength and extremely high extensibility, giving the fabric its outstanding mechanical properties. However, the properties of silk are influenced not only by the amino acid sequence of the proteins that make it up, but also by the way in which individual proteins interact with one another to form a macroscopic thread. The structure of spider silk is still being studied, but it is hypothesised that the protein fibres organise themselves hierarchically into different structural levels. We can imagine the structure of silk as a series of Russian dolls: every larger structure contains a smaller one, all the way down to the sequence of amino acids of the individual proteins, and it is this stratified structure that yields spider silk's complex and intelligent response to environmental conditions.[1]

In short, the silk's astonishing ability to adapt its mechanical response to the stimuli it receives can be understood as the result of its structure: with a molecular composition that is partly rigid and partly amorphous, i.e. part crystalline and part disorderly, silk is neither a solid nor a liquid, but a material with hybrid characteristics. The presence of mobile structural elements makes it similar in some ways to a viscous liquid, capable of transferring the kinetic energy of a macroscopic mechanical stimulus—such as the impact of an insect—to its own molecules, which, moving more or less independently of one another, are able to dissipate this energy rapidly in the form of heat, thus preventing the silk from breaking, as would happen in the case of a completely rigid material. At the same time, though, the structural elements of the silk, at the moment they are subjected to tension, can organise themselves within the thread in an orderly manner, maximising their reciprocal interactions and producing an immediate reinforcing effect which makes the thread stronger and allows the spider to save itself from a sudden fall. This complex response occurs in a fraction of a second, and is not coordinated by any external 'controller'; it emerges as a result of simple chemical and physical interactions between the molecules of the material.

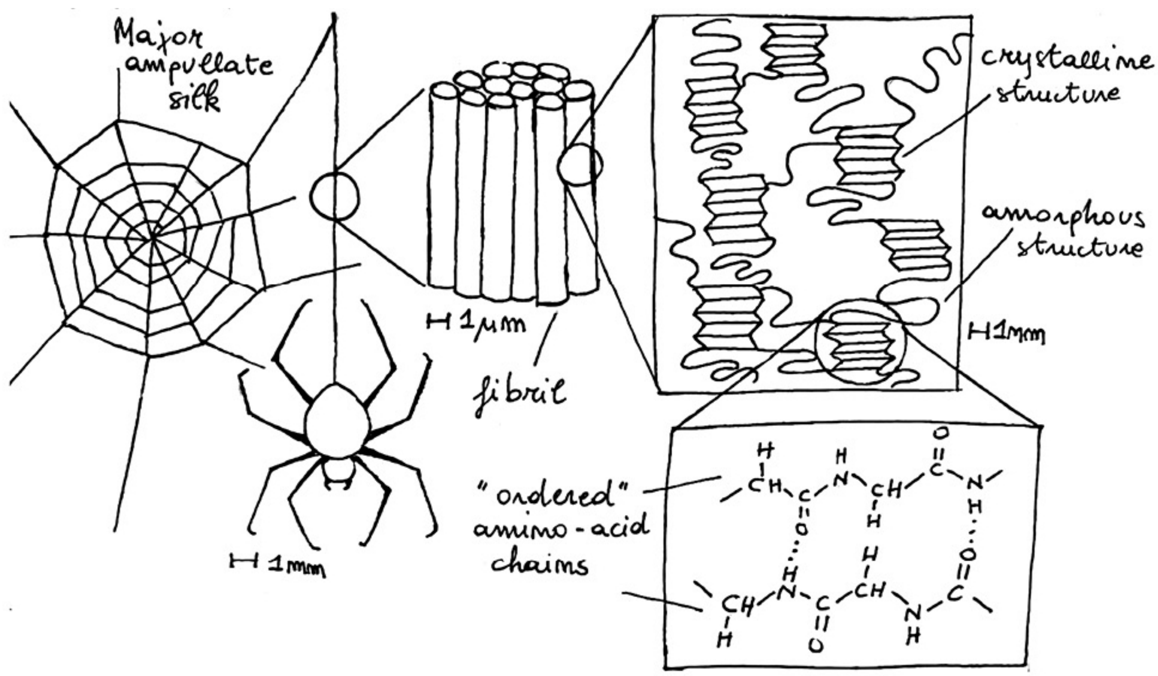
Similarly, the threads of spider silk also radically modify their own structure when exposed to water or ambient humidity, shortening and considerably increasing in diameter. This phenomenon is called *supercontraction* and, although its function has not yet been fully clarified, it is yet another of spider silk's fascinating properties. When water is absorbed by the silk thread, the protein chains of which it is composed fall out of alignment, returning to their ordered fibrous structure only when they dry out. As supercontraction causes the silk fibres to stiffen considerably, it is possible that this structural change is necessary to support the weight of raindrops or dew deposited on the web daily. It has also been proposed that this structural change is a kind of self-repair mechanism. The microscopic structure of the silk is destroyed during the absorption of water, giving the proteins greater freedom of movement and allowing the formation of new physicochemical interactions during drying: in this way, the silk threads, subjected to the stress caused by the capture of insects, would be able to regenerate the damaged parts of their structure thanks to the morning dew. The capacity of spider silk to regenerate its structure on its own is not only an enviable ability—research into new synthetic materials capable of self-repair is an area of ongoing development—but also demonstrates once again its ability to respond intelligently to environmental stimuli.



In the late 1800s, French missionary Jacob Paul Cambou built a hand-driven machine to extract silk from up to twenty-four spiders at a time.

But perhaps the most amazing aspect of silk is the mechanism by which it can transform itself from liquid to solid in a fraction of a second. This phenomenon is currently one of the most controversial, because while it is already possible to produce spider silk proteins in the laboratory using genetic engineering, transforming them into the ultra-resistant fibres used by spiders in nature would be a difficult task.[2] Contrary to what one might suppose, the glands in the spider's belly do not contain silk threads ready to be stretched into a web, but a highly concentrated aqueous solution of proteins not yet assembled into their fibrous structure. In our daily experience we are used to thinking that the transformation of a material from liquid to solid occurs by cooling, as when a molten metal wire solidifies at room temperature, or through evaporation of a solvent, as for example when we apply a varnish and let the air dry it. The solidification mechanism of spider silk, however, is unlike either of these processes. The process of fibre formation is not yet completely clear, but it is possible that it is triggered by an acidity gradient within the spider's glands. Suppose we have a dense, liquid solution to which we need only add a few drops of vinegar and instantly, threads of the most resistant material in nature emerge from the solution. How can a stimulus as simple as a change in acidity determine the formation of such a complex functional structure?

The formation mechanism of the silk is not quite as simple as this, and is probably also determined by other factors including the force applied to the thread as it is extracted from the gland through the spider's spinneret. What is interesting, however, is that the structure of the silk—the 'Russian doll' structure described above—is capable of *self-assembling* so long as it is provided with the appropriate environmental conditions. Whereas in an ordinary fabric each thread has to be woven together individually with the others, Arachne's web—once the weaver has been transformed into a spider—builds and rebuilds itself: its molecular 'threads' are able to organise themselves autonomously, creating an intelligent and dynamic weave, as if a tangled ball of cotton thread were transformed into a perfectly ordered fabric by means of a simple change in the environmental conditions.



Chemical structure and hierarchical morphology of spider silk.

---

1. J.L. Yarger et al., 'Uncovering the Structure-Function Relationship in Spider Silk', *Nature Reviews Materials* 3:3 (2018), 18008.

2. A. Rising and J. Johansson, ‘Toward Spinning Artificial Spider Silk’, *Nature Chemical Biology* 11 (2015), 309–15.

Weaving the Future

In her book *Zeros And Ones,* the philosopher Sadie Plant examines the relationship between weaving and new technologies, especially in the context of computer science and cybernetics. She links the idea of *soft technology* to the concept of *software*, i.e. programs that are able to perform abstract processes via a material substrate. According to Plant, fabric and software are based on a similar principle:

> [T]extile images are never imposed on the surface of the cloth: their patterns are always emergent from an *active matrix*, implicit in a web which makes them *immanent to the processes from which they emerge*.[1]

In this sense, it is never possible to separate the abstract content of the software from the material process that produces it, in the same way that it is never possible to separate the pattern we see in a tapestry from the interweaving of the threads that make it up. Although the concept of software does not belong to the domain of materials science, the thought that Plant expresses here is also applicable to the *soft* material that makes up the spider's web, and to many other smart materials. The ability of a material to construct and modify its own structure autonomously suggests a form of intelligence which, unlike the centralised form we are used to thinking about, is produced continuously within the dynamic fabric of chemical and physical relations between the elements that make up the material.

If we had to choose an exemplary material, a specimen we could use to indicate the direction we ought to take when designing the materials of the future, spider silk would certainly be first in line. In addition to its oft-cited mechanical resistance, it is also able to adapt to the environment, to assemble itself independently and to regenerate its structure; it is completely biodegradable and, if we were able to discover all of its secrets, could be produced in ordinary environmental conditions from an aqueous solution with minimal energy expenditure. Compare this with nylon 66, the synthetic fibre omnipresent in our clothes, which is also a polymer made up of molecular building blocks held together by bonds essentially identical to those that bind together the amino acids of spider-silk proteins. However, not only are the 'building blocks' of nylon, two molecules called hexamethylenediamine and adipic acid, petroleum derivatives; combining them to form nylon requires a reaction that only works at a pressure of 18 atmospheres and a temperature of 275 degrees centigrade. But energy efficiency in fibre production is not the only reason for interest in spider webs. Several studies have proposed using spider silk in biomedical applications as a support for tissue regrowth; supercontraction could even be exploited to produce artificial muscles capable of performing work in response to a simple environmental stimulus. More generally, science has always looked to nature as a source of inspiration for new technologies, an approach known as *biomimicry*: the structure of a spider web, composed of different microscopic elements capable of cooperating with one another to form a complex material, could be an inspiration for the design of synthetic materials with equally startling properties, and with applications yet to be imagined.[2]

In a certain sense, spider history has fared better than the history of human weavers of the past. In certain cases, the remains of one of their ancient ancestors have been permanently trapped in amber, offering us a privileged glimpse into a lost world; and where these finds were not enough, evolution has left the story of their ancient art written in the genes that code for silk proteins. The remains of Palaeolithic fabrics, on the contrary, have been completely destroyed, and there is no genetic archive to preserve their history for us. Human technology is far more fragile and volatile than evolution by natural selection, subject as it is to social and cultural forces that continuously influence its direction. Science journalist Leslie Brunetta and biologist Catherine Craig, in their book on the evolution of spider silk, argue that the extraordinary evolutionary success of spiders has been determined by their ability to exploit relatively small genetic mutations to obtain enormous immediate benefits in the functional properties of their silk proteins.[3]

The idea that a very small chemical change in a material can determine the survival of an entire species is an equally fascinating concept when applied to human technologies: very often, the impact that a new material has on our future extends far beyond its molecular structure, involving numerous aspects of our life and culture. Precisely for this reason, it is up to us to try to envision a world in which a material as intelligent as spider silk could play a significant role and realise its full potential. From this perspective, it may not be enough to continue thinking about technology in the same way we always have done: if when confronted with a complex and refined material such as spider silk, all we can think about is its ability to stop an aeroplane in flight, the principal limitation is obviously not technical feasibility but lack of imagination.

Contemporary materials science is always battling against this over-simplistic, hyper-optimistic view of the opportunities that new materials can afford us. The most recent and blatant example of this misunderstanding has concerned the discovery of graphene, the two-dimensional, nanometric carbon-based material that was first isolated at the University of Manchester in 2004 and has quickly become a symbol for the advancement of nanotechnology. As a researcher in the field of nanomaterials, I am often asked why graphene has not changed the world yet. In light of graphene's outstanding mechanical, electrical and thermal properties, promises of space travel, boundless energy storage and superstrong body armour have flourished in pop-science articles and books over the last decade. But fantasy tales of 'wonder materials' tell us very little of the real ways in which advancements in materials science can impact our lives and culture, and often result in widespread public frustration and disappointment. Nowadays, the most promising applications of graphene do not involve its use as a standalone, super-performing material, but rather focus on its integration into more complex structures, creating hybrid, composite materials with enhanced properties.[4] The behaviour of such composite materials closely resembles the mechanisms though which spider silk achieves its outstanding characteristics: dynamic self-organisation in complex material systems is gradually surpassing the need for one single, indestructible material.

Without a doubt, spider silk is one of those exceptional materials which, in materials science, is defined as *soft*: a term which includes all non-rigid, often polymeric materials with characteristics that place them somewhere on the spectrum between solid and liquid. *Morbido*, the word for 'soft' in my native Italian, suggests a more negative connotation, associating this lack of rigidity with something sick and defective: its root is the Latin word *morbus*, which means *disease* (hence the English word 'morbid'). A connotation that perhaps is not just etymological, but also tells us something about the material culture in which we are immersed. Spider silk is intelligent precisely because of its softness, which allows it to modify its structure in response to the environment. And rethinking technology in soft terms is an at once technical and cultural challenge, one that we can only address by developing an integrated vision of technology and its role in our lives.

1. S. Plant, *Zeros And Ones: Digital Women and the New Technoculture* (London: Fourth Estate, 1998), 67 (emphasis mine).
2. X.Y. Liu and J.-L. Li, *Soft Fibrillar Materials: Fabrication and Applications* (Weinheim: Wiley-VCH, 2013).
3. L. Brunetta and C.L. Craig, *Spider Silk: Evolution and 400 Million Years of Spinning, Waiting, Snagging, and Mating* (New Haven, CT: Yale University Press, 2010).
4. T. Barkan, 'Graphene: The Hype Versus Commercial Reality', *Nature Nanotechnology* 14 (2019), 904–10.

5

What the Future is Made Of

Ariadne: My king, my father, that's how heroes and gods see. What do you see during the day if not the night, fear, and the Minotaur that you have threaded from insomnia's film? Who cultivated his ferocity? Your dreams. Who brought him the first pack of young men and women, torn away from Athens by terror and the glory of sacrifice? He is your furtive creation, like the shadow of a tree is the vestige of a chilling night.

JULIO CORTÁZAR, *THE KINGS*

Minds in the Web

The ‘strange minds’ we have explored, from *Physarum polycephalum* to octopi, from spider silk to artificial smart materials, call into question the conventional conception of the human mind as a centralised structure, organised around a single ‘command centre’ from which instructions for the control of the organism are sent out, and through which information about the external environment is collected. On the contrary, these minds owe their intelligence to their decentralised and diffused structure, in which a multiplicity of simple mechanisms combine to elaborate a complex response to the world in which they are located. It is therefore necessary to question, once again, the meaning of the word ‘intelligence’ when we use it to define non-human organisms and materials: it is now clear that although the mind, at least in our everyday perceptions, seems to function like a mirror, first building a unitary representation of reality and then acting within it, there are also minds that function in a *non-representative* way, without any need to build a reflective image of themselves and the world, and yet still manage to exhibit intelligent behaviour, adapting to their environment in response to external stimuli.

Diverse as they are, all of these minds are united by the fact that they consist of a very large number of elements which, considered individually, are ‘stupid’, i.e. do not exhibit the properties that the system as a whole manifests. The most important lesson to be learnt from these systems is that *intelligence emerges from relationships*: a set of simple interactions within a collectivity of elements can bring out properties that the individual components of the system alone did not possess. Intelligence may then be considered an emergent property of those systems we have learned to call complex systems, in which a multiplicity of parallel relations produce different forms of self-organisation from below. The word *parallel*, in this context, serves to underline the fact that within these structures there is no pre-established hierarchical organisation: there is no ‘control room’ that directs the behaviour of the parts and there is no instruction manual that tells the individual components how to organise themselves with respect to one another. What is interesting about this vision of intelligence is that it does not depend on the specific nature of the components that constitute it, and for this reason it has been observed across disciplines, in many different areas: from quantum physics to biology, from psychology to information technology. In the case of materials science, the nanotechnological approach, focused on static and dynamic self-organising processes, makes it possible to exploit the emergent properties of complex systems to design new materials capable of behaving in an increasingly intelligent way. Spider silk is a perfect example of natural nanotechnology that exploits the complexity of its microscopic structure to optimise its interaction with the environment.

One might wonder why, if this vision of intelligence is so transversal and interdisciplinary, we should pay special attention to the existence of 'intelligent materials', a case that may seem marginal in an extraordinarily vast universe of other minds, natural and artificial. Many answers can be given to this question. As we have seen, on the one hand, studying the capacity of non-living matter to organise itself and receive stimuli from the outside world can help us find a continuity between the world of matter, which we usually consider inert, and the world of life, populated by dynamic structures capable of maintaining their own internal organisation, growing and replicating themselves. In discovering that the phenomena of self-organisation are not exclusive to life, we realise that our existence as living beings is not an exception, but just another confirmation of the vitality of matter that composes us, opening us up to the possibility of encountering forms of 'life' completely different from those that we know.

The search for alien life or the creation of completely artificial organisms may seem totally science-fictional propositions and, in the context of this essay, we have used them mainly as 'thought experiments' or 'proofs of concept' that help us to explore the outer reaches of an idea—that of the intelligence of materials—by taking it to its most radical consequences. But even if in most cases they are not (yet) able to completely assemble and replicate themselves, the materials that surround us in our daily reality do already participate very actively in the construction of the world in which we live. The materials that we use in our technologies, from the fabrics of our clothes to the silicon of our solar panels, from the cement of our houses to the Kevlar of the International Space Station, are an integral part of our culture, our history and, above all, our future. For this reason, the position we decide to take with regard to the materials that make up our world is of fundamental importance. Our intelligence and the intelligence of the materials we use are connected, networked, and exert influence on one another to determine the shape of our reality. Is there a way to think of the materials that surround us not as passive objects, but as an active part of our world?

An answer to this question may be found in the extraordinary material from which we started and in its relationship with the mind of the animal that produces it. In a 2017 article, biologists Hilton Japyassù and Kevin Laland proposed that the spider is one of the very few animals, apart from humans, capable of extending its mind outside of its body.[1] In Chapter 2 we encountered the use of the concept of extended cognition, or the extended mind, to describe humans' ability to 'delegate' a part of their cognitive work to the objects around them, for example using computers and smartphones to communicate with our fellow humans, calculators to facilitate arithmetic calculations, or notebooks as an extension for long-term memory. Similarly, Japyassù and Laland propose that the spider uses the web it builds as an extension of its perceptual organs and its brain. According to them, since the spider is a predator living in a very complex environment, and since maintaining a highly developed central nervous system has an extremely high energy cost, evolution has 'chosen' to transfer part of the spider's intelligence, which the animal needs to hunt and orient itself in space, to a material external to its body.

The spider is almost completely blind and has a rather simple central nervous system, which makes it incapable of storing long-term information or constructing a mental representation of its surroundings. In spite of this, it is able to orient itself within the complex three-dimensional space it inhabits, building with its own silk perfectly symmetrical structures that are of enormous dimensions relative to its own body, something that would be very demanding even for a human individual. The way in which the spider manages to accomplish such a complex task is determined precisely by its ability to use silk to draw a geometric map of the space around it, using it as a sort of spatial memory external to its body. We have already encountered a similar behaviour, although with significant differences, in polycephalic slime's ability to map and explore its environment by depositing chemical traces of its passage which act as a memory external to the body. According to Japyassù and Laland, 'the spider, by relying on the previous threads as external, long-term memory devices, probably requires less CNS long-term memory than other similarly complex animal activities'.[2] In this sense, it becomes entirely impossible to locate the boundary between the spider's mind and its web.

But the cognitive relationship between spider and web is not limited to determining the animal's orientation in space. The web acts as a genuine sense organ for the spider, transmitting and amplifying the vibrations of the prey trapped in its threads. This capacity for transmission is closely related to the microscopic structure of the silk, its thickness, and the tension given by the spider to the threads of the web. The authors report that hungry spiders increase the tension in their webs to increase their sensitivity, allowing them to respond to smaller prey that they would usually ignore. Not only that, but by artificially altering the tension in certain areas of the web, the experimenters were able to alter the spider's mind, focusing its attention on the most sensitive areas. 'In this sense', they write, 'web threads cannot be understood as passive transmitters, or even passive filters of vibratory information. Thread properties are adjustable and thus can process the same information in different and adaptive ways.'[3]

From this perspective it is clear that the relationship between the spider and its silk is a very tightly-woven one. On the one hand, the spider modifies its perception of the world by altering the canvas both from an engineering point of view (i.e. modifying its shape and tension), and a nanotechnological point of view, improving and adapting its microscopic chemical structure during evolution to make it more functional for its own purposes. On the other hand, the silk itself, as a complex and sensitive material, influences the way the spider perceives the world and acts upon its environment, to the point where the smallest mutation in the chemical structure of silk can bring about a radical change in the spider's behaviour. It is precisely this mutual influence between *animal mind* and *material mind* that allows the spider to succeed in its environment; to think of silk simply as a passive object which the spider uses to survive is an oversimplification of this complex reciprocal relationship.

Our cultural relationship with the materials we use in many ways resembles that between the spider and its silk. The web the spider builds is both an artificial technology and a natural environment, both a tool and an integral part of the subject that produces it. We too are defined as human beings by our ability to shape our environment using the materials around us, which in turn influence our reality and our future. We might perhaps imagine that our relationship with the materials we use is less intimate: after all, the structure of silk is written in the spider's genes, while our materials seem more separate from us: it is, however, increasingly evident that the future of our species is also inextricably intertwined with the materials we decide to use to build it. In this sense, the concept of the *web or network* may be used as a transdisciplinary category to address our relationship with the materials of the future. From a technological point of view, designing materials with a relational internal structure, i.e. a network of numerous components that participate in a fabric of parallel and reciprocal connections, allows us to build technologies that are increasingly intelligent and sensitive, like spider silk. At the same time, from a cultural point of view, replacing a vertical vision of our relationship with technology in which human beings univocally define the relationship with their own instruments, with the idea of a network of parallel interactions between human and non-human agents, in which the materials we use can in turn influence our relationship with the world, allows us to extend our mind and open ourselves up to a more ecological vision of our relationship with the environment around us.

---

1. H.F. Japyassù and K.N. Laland, 'Extended Spider Cognition', *Animal Cognition* 20 (2017), 375–95.
2. Ibid., 385.
3. Ibid., 381.

Arachne 2.0

One of the most interesting issues raised by the study and synthesis of new materials concerns the relationship between nature and technology. As we have discovered, many new artificial materials are characterised by the ability to enter into relation with living organisms, to mimic the characteristics of natural materials, and to assemble into hybrid objects in which nature and technology blur and blend together. Here again we can use spider silk as a 'model material' to reflect on the hybridisation between nature and technology. In itself, the spider's ability to weave its own web could be understood simply as a natural fact and put down to the difficult-to-define idea of *instinct*; but at the same time, the spider's web is the technological tool the creature uses to modify the environment around it.

Since the birth of nanotechnology, carbon has been the most important element for the synthesis of new materials on the nanoscale. Graphene and related materials, such as carbon nanotubes, owing to their mechanical, thermal, and electrical properties, are now considered the nanomaterials par excellence. Graphene is a two-dimensional material made up of a graphite 'sheet' in which carbon atoms are arranged to form hexagonal cells. Nanotubes have the same chemical structure as graphene, but are 'rolled up' on themselves to form straw-like tubes. The interaction between these artificial materials and spider silk, owing to their very high surface area, produces an extraordinary reinforcement, generating what in materials science is called a *nano-composite*: a dispersion of nanometric particles, usually inorganic, in a matrix, usually organic. Nanomaterials such as graphene are often not used alone, but find their principal applications in the preparation of such nanocomposites, where nanoparticles of the material are combined with other substances to form hybrid materials with improved or completely new properties. A study in 2017 analysed the effect on the physical characteristics of spider webs when they are exposed to certain artificial nanomaterials,[1] and showed that, after ingestion of graphene and carbon nanotubes, spiders are able to weave a silk up to ten times more tenacious, i.e. ten times more capable of absorbing the energy of an impact, and three times more resistant than ordinary silk. The material obtained from this process yields a fibre with some of the most extreme mechanical properties ever recorded, surpassing even the most advanced synthetic fibres. This nanotechnological silk is one of the first and most fascinating examples of a *bionic material*, i.e. a hybrid material obtained by combining a natural material produced by a living organism with an artificial material. Here the spider's unparalleled ability to weave its web, so difficult to reproduce in the laboratory, is integrated with some of the most innovative man-made materials. Spider silk modified with artificial nanomaterials could also be used for electronic and robotics applications, where its resistance, combined with the electrical conductivity imparted by the nanoparticles dispersed within it, could allow us to produce circuits, sensors, and tiny artificial muscles. In fact, by exploiting the spider web's ability to contract and extend as the ambient humidity varies, it is possible to use the electrical resistance of the bionic silk thread to heat and cool it in a controlled way, obtaining contractions whose capacity to perform mechanical work, if considered in proportion to the very fine diameter of the fibre, would far exceed that of human muscles.[2]

The idea of using innovative materials capable of forming an extensive and dynamic interface with biological structures is attracting growing interest. Because of their scale and properties, these carbon-based nanomaterials transform nature as we know it, even potentially becoming part of our own bodies. One example of this concept is a newly designed prosthetic material for spinal lesions. A 'sponge' made up of carbon nanotubes, when introduced inside a damaged area of the spine, could be an effective support for the regeneration of neurons: not only is it structurally resistant, owing to the mechanical properties of carbon nanotubes, but it also integrates the functionality of nerve cells owing to its outstanding electrical conductivity.[3] The carbon nanotubes used are produced following a self-assembly approach which exploits the ability of carbon atoms to self-organise into precise structures out of a chemical hydrocarbon vapour. Here the intelligence of inorganic matter intertwines with living intelligence in an extraordinary hybridisation of life and chemistry that could potentially find a role to play in even the most intimate mechanisms of our own nervous system. These examples highlight one of the most interesting aspects of nanotechnology, namely the possibility of acting on the same level as biological life. No doubt this also presents risks, many of which will need to be clarified before we can feel comfortable using these as wide-scale technologies: owing to their very small size, nanoparticles can penetrate undisturbed into our bodies, where, depending on their chemical nature and structure, they could cause irreversible damage; the difficulty of filtering and recovering nanoparticles once they have been dispersed into the environment makes the problem of using nanotechnologies yet more complex.[4]

From a more conceptual point of view, materials science brings life and technology onto an equal footing, thus affording us the opportunity to renegotiate our relationship with the technologies we build. The question of where nature ends and technology begins may perhaps seem trivial, but the ever-expanding interface between new materials and our bodies shows that it is precisely on the borderline between these two worlds that the most interesting technological potentials are realised, and it is in this hybrid space that applied science, so often excluded from the more theoretical discussions on the role played by science in our world view, can and must also open onto an epistemological and political dimension. Undoubtedly, the development of science and technology has often provided the pretext for bolstering the cultural paradigm that places humans in a position of domination over the living and non-living matter that surrounds them, with often catastrophic consequences. This domination is rooted in the possibility of drawing insuperable boundaries between what makes us human and what is radically different from us. On the other hand, any appeal to the concept of nature, whether to protect it or to exercise dominion over it, ends up reaffirming the distance that separates us from it, relieving us of the responsibility of questioning our position in the world and our use of technology. In contrast to this approach, the construction of hybrid technologies that transcend the presumed boundaries of what is natural and what is technological can help us establish a fruitful dialogue with the objects and organisms with which we share our culture, calling into question the idea that there is only one legitimate view of the universe we inhabit.

Like spiders in their webs, our knowledge of reality is shaped by the tools and materials we use to relate to the environment. If the mind of the spider extends into the depths of the microscopic structure of its silk fibres, what does the spider-cyborg dream of, asleep in its bionic graphene-wired web? What unknown prey's vibrations reach the neurons in its eight legs? How will information flow through our spine when its marrow is intertwined with carbon nanotubes? Such strange hybridisations reveal the transience of the boundary that separates our consciousness from the world around us, and our objects of study from the subject that studies them. By creating completely new tools and environments, the technology of new materials does not just allow us to discover a pre-existing nature that reveals its secrets to us; it actively contributes to the construction of new realities. Since our mind, like that of the spider, is inextricably intertwined with our technologies, building new materials means above all inventing new ways of relating to the world, new ways of seeing and feeling the matter around us, produced through the encounter between our intelligence and other minds.

---

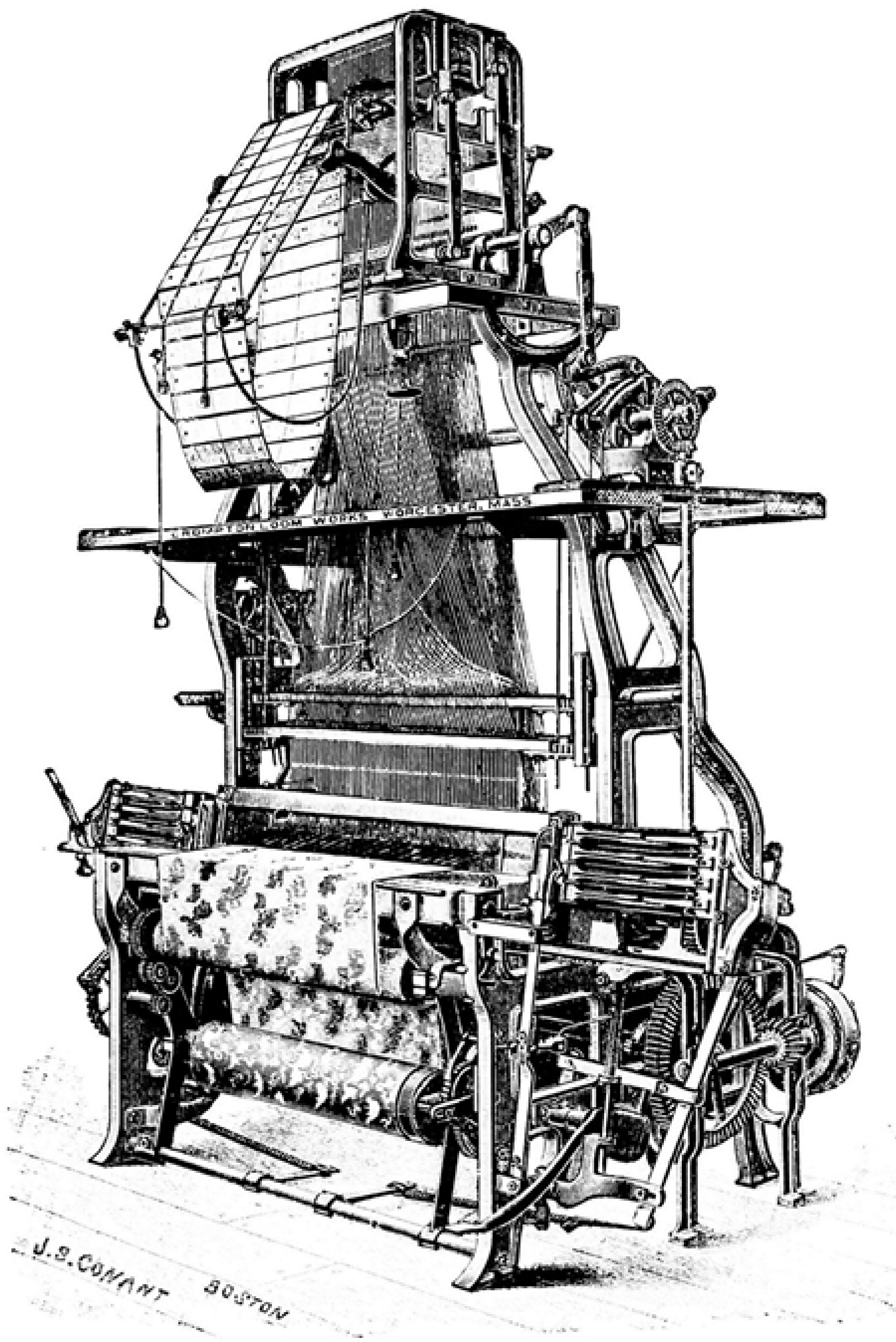
1. E. Lepore, et al., ‘Spider Silk Reinforced by Graphene or Carbon Nanotubes’, *2D Materials* 4:031013 (2017).

2. The construction of such a device, obtained from spider silk threads covered with carbon nanotubes, was reported in the magazine *Nature Communications* in 2013 (E. Steven et al., ‘Carbon Nanotubes on a Spider Silk Scaffold’, *Nature Communications* 4:2435 [2013]).

3. S. Usmani et al., ‘Functional Rewiring Across Spinal Injuries via Biomimetic Nanofiber Shelves’, *Proceedings of the National Academy of Sciences* 117:41 (September 2020), 25212–18.

4. An overview of the potential risks of nanoparticles for human health can be found, for example, in M.M. Sufian et al., ‘Safety Issues Associated with the Use of Nanoparticles in Human Body’, *Photodiagnosis and Photodynamic Therapy* 19 (2017), 67–72.

Weavers of the Future



Jacquard Loom, illustration from *The Popular Science Monthly*, 1891.

Arachne, the mythical weaver whose story we told in the opening pages of this book, embodies the idea of a technology that intertwines perfectly with she who produces it. Not only does Arachne weave the threads of her tapestry with incredible skill, producing complex structures from the mutual interaction of simple elements, she also transforms herself into a spider, blending herself and her loom into a single hybrid body that incarnates the indissoluble weave between mind, body, technology, and nature. Sigmund Freud, in his *Introduction to Psychoanalysis* in 1932, suggests that women, despite their general inability to participate actively in the development of human civilisation, have made at least one contribution to the history of technology:

> It seems that women have made few contributions to the discoveries and inventions in the history of civilization; there is, however, one technique which they may have invented—that of plaiting and weaving. If that is so, we should be tempted to guess the unconscious motive for the achievement. Nature herself would seem to have given the model which this achievement imitates by causing the growth at maturity of the pubic hair that conceals the genitals. The step that remained to be taken lay in making the threads adhere to one another, while on the body they stick into the skin and are only matted together.[1]

According to Freud's vision, the ability to weave is inherent in women's nature, because women learned weaving by imitating the natural weave of hair which, according to the psychoanalyst, 'hides' the 'lack' of the penis that every woman unconsciously desires. Although, on the one hand, this is one of the most misogynistic pages in the history of psychoanalysis, in which all contribution to technology and science is completely denied in the name of an inscrutable biological destiny, Freud is nonetheless correct in at least one respect: that weaving and femininity are connected in a deeper way than it may seem. Not only has weaving made an incalculable contribution to the development of our culture, it has more or less explicitly been a model for many of the most advanced technologies we use today, from artificial intelligence to nanotechnology. Addressing the relationship between cybernetics, computing, and femininity, Sadie Plant focuses on the central yet often neglected role played by weaving in the birth of the first computers and the development of technology as a whole. As she states:

> Perhaps weaving is even the fabric of every other discovery and invention, perhaps the beginning and the end of their history. The loom is a fatal innovation, which weaves its way from squared paper to the data net.[2]

To which we might add that, as we have seen, weaving is an art that begins with the loom and ends up intertwined with the intelligence of our most advanced nanomaterials. While this does not, of course, mean adhering to the idea that women possess some kind of exclusive capacity rooted, as Freud argued, in the female psyche, it does highlight the need to modify our cultural approach to technology.

Many contemporary feminist theorists have questioned the relationship between nature and culture, reflecting on the possibility of negotiating a new relationship between science, the matter it studies, and the technologies it builds. The reason why femininity and technology are so often considered incompatible in our patriarchal civilisation is rooted in the idea that science and technology are tools that man uses to exercise a form of violent domination over nature. From this cultural perspective, an active subject, the man-scientist, acts upon a passive object, matter, giving it form and bending it to his own will. If we were to exemplify this approach in one of the most primitive human technologies, the process of splintering a stone, transforming it into an axe or arrowhead, is a good embodiment of the idea that matter is an essentially inert object which does not work with, but opposes, our attempts to modify it to our advantage. This paradigm of man's dominion over matter, which places him in the privileged position of having to give shape to an essentially blind and stupid substance, then also exerts its effects on the social and political level: everything that is perceived as 'other'—that is, in some way, 'less human'—becomes an object of domination and violence. Is it possible to imagine a technological paradigm in which matter actively participates in its own process of transformation?

According to the philosopher Luce Irigaray, modern Western metaphysics is based on the idea of a universe made up of solid bodies in rigid interaction with each other. This vision is reflected in the idea of the interaction between bodies as a collision or clash rather than a relationship: the only thing these rigid objects can do is bump into each other, a bit like the process of chipping a stone to turn it into a tool. On the contrary, Irigaray argues that the substratum of reality is essentially fluid, i.e. made up of bodies without rigid boundaries, which interpenetrate and mix with one another.[3] As in the weave of a fabric, individuals intertwine with one another to produce a network in which individual boundaries blur and individuals become indistinguishable. This continuous interpenetration can serve as the basis of an understanding of the material environment in which we are immersed and the other human beings around us as part of a single network of relationships, one which for this reason also implies a shared responsibility to construct an ethics based on the recognition of the other. In this sense, weaving embodies a relational and feminist vision of technology as an indissoluble interweaving of human, animal, and material agents.

While exploring the boundary between organic and inorganic we have already met the figure of the cyborg, the cybernetic organism which, according to Donna Haraway, could constitute a new paradigm for technology, capable of overcoming the binary logic that separates nature and culture. After all, our journey through the world of new intelligent materials has brought us to the confrontation with many ‘monsters’, some mythological and some technological, some natural and others artificial: from the Lernaean Hydra to the Golem, from polycephalic slime to bionic spiders, from Frankenstein’s creature to self-replicating organic molecules. What all of these strange organisms have in common is the challenge they pose to our customary notions of what belongs to the natural order of things; they inhabit the borderland between life and death, mind and body, technology and nature.

‘It is not just that science and technology are possible means of great human satisfaction, as well as a matrix of complex dominations’, writes Haraway in her famous *Cyborg Manifesto*. ‘Cyborg imagery can suggest a way out of the maze of dualisms in which we have explained our bodies and our tools to ourselves’.[4] Haraway’s scientific training, which led her to address the concept of organism in the history of biology, naturally leads her to the conclusion that there is ‘There is no fundamental, ontological separation in our formal knowledge of machine and organism, of technical and organic’.[5] In fact, as we have seen, all of these categories are extremely fluid, and can merge into each other with great ease. From Haraway’s radical perspective, while the increasingly pervasive hybridisation of technology and life might frighten us, and is often rejected by more traditional feminisms as an expression of man’s technological domination over nature, this prospect actually harbours potential for emancipation:

> That is why cyborg politics insist on noise and advocate pollution, rejoicing in the illegitimate fusions of animal and machine. These are the couplings which make Man and Woman so problematic, subverting the structure of desire, the force imagined to generate language and gender, and so subverting the structure and modes of reproduction of ‘Western’ identity, of nature and culture, of mirror and eye, slave and master, body and mind.[6]

The link between a certain strand of feminist political thought and technology passes via a renegotiation of the scientific and cognitive gaze upon nature. This does not mean, however, that technology allows us to shape reality at will; rather, it means that our experience of the world is always intertwined with our tools and the materials we use, which form a dense and inextricable weave with our minds. In other words, our scientific knowledge of reality is not a more or less perfect mirroring of a world of passive and distant objects. On the contrary, knowledge of reality, if not reality itself, is produced in the *encounter* and the *relationship* between ourselves and our object of study. This is the perspective adopted by Karen Barad, who, starting from an analysis of the role of the measurement process in quantum physics, arrives at a new definition of the human relationship with matter.[7] In the background of Barad's thought is the essential and most well-known problem of quantum mechanics, the problem of indeterminacy. Without entering into the technical details of this problem, whose consequences have now become common knowledge, the principle of indeterminacy implies that in the study of quantum objects it is impossible to separate the process of measurement via which we *know* the object we are studying, from the *physical nature* and *properties* of the object itself. In other words, quantum objects seem to behave differently, typically as waves or particles, depending on *how we look at them*, i.e. depending on the instrumental apparatus with which we choose to study them.

In the thinking of the physicist Niels Bohr, one of the fathers of quantum mechanics, this problem is solved by resorting to the concept of complementarity, according to which the behaviour of the studied quantum object cannot be separated from the measuring apparatus that studies it. Setting out from this idea, Barad proposes a new vision of the physical universe as no longer constituted by single objects that pre-exist their scientific investigation, but rather as a network of relations within which physical phenomena take shape and acquire meaning. According to Barad, the concept of matter 'refers to the materiality and materialisation of phenomena, not to an assumed, inherent, fixed property of abstract, independently existing objects':[8] matter is the process that results from an encounter rather than an *a priori* existing reality. In this vision and process of matter, the object being studied and the mind of the scientist who studies it participate symmetrically and cooperatively in the definition of knowledge. The concept of *entanglement*, which in quantum physics indicates the indissoluble correlation between two particles of the same system, is repurposed by Barad as a more general paradigm of the human relationship with matter, a relationship in which there are no defined boundaries but only a continuous and reciprocal influence. This perspective on science then presents an opportunity to question the rigid separation between subject and object that runs through the history of modern Western thought:

> There is no *res cogitans* that inhabits a given body with inherent boundaries differentiating self and other. Rather, subjects are differentially constituted through specific intra-actions. The subjects so constituted may range across some of the presumed boundaries (such as those between human and nonhuman and self and other) that get taken for granted. Knowing is a distributed practice that includes the larger material arrangement. To the extent that humans participate in scientific or other practices of knowing, they do so as part of the larger material configuration of the world and its ongoing open-ended articulation.[9]

Abandoning the strange world of quantum particles to return to the familiarity of our spider webs, the relational vision of matter that Barad applies to theoretical physics can very easily be extended to the applied sciences and, in the light of what we have seen above, lends itself in particular to the case of intelligent materials. For in this context also, we are dealing with objects which, although very different from Bohr's quantum particles, *actively participate in the construction of the reality in which they are immersed*. In particular, we have already highlighted how chemistry and materials science propose an essentially synthetic approach to the study of matter, in which the product of the cognitive process is always also the product of a creative and productive process which leads to the birth of new bodies. The synthesis of a new material is never the result of a univocal process determined by the human experimenter, because it always exploits the ability of matter to organise itself spontaneously, bottom-up. The challenge of synthesis, then, is not so much to dominate matter, but rather to understand 'what a material can do'—that is, to reveal its intrinsic vitality and its deepest intelligence, as manifested in its relationship with us.

Among the authors who have embraced this relational vision of matter and technology is the philosopher Jane Bennett who, in her book *Vibrant Matter: A Political Ecology of Things*, proposes what she calls a 'vital materialism'. According to Bennett, the inorganic materials and bodies around us are also endowed with an intrinsic vitality, which is manifested in their ability to actively participate in our world. From the perspective of this author, it is not possible to imagine a material environment separate from our human culture: on the contrary, culture and environment are connected on a single horizontal ontological plane without pre-established hierarchies, and every agent participating in it, from humans to animals to the objects we use in our daily lives, is capable of actively communicating with every other agent.[10] To describe this profound connection, rather than using the term 'matter', a word that in philosophical language has taken on the meaning of a passive object rigidly separated from the human subject, Bennett prefers to speak of *material configurations*:

> I am a material configuration, the pigeons in the park are material compositions, the viruses, parasites, and heavy metals in my flesh and in pigeon flesh are materialities, as are neurochemicals, hurricane winds, *E. coli*, and the dust on the floor. Materiality is a rubric that tends to horizontalize the relations between humans, biota, and abiota. It draws human attention sideways, away from an ontologically ranked Great Chain of Being and toward a greater appreciation of the complex entanglements of humans and nonhumans. Here. the implicit moral imperative of Western thought —'Thou shall identify and defend what is special about Man'—loses some of its salience.[11]

By placing the relational fabric of matter at the centre of its ontology, this new feminist and materialist thinking invites us to enter into a direct relationship with the technologies that make up our world, to understand their impact in a deeper way and, if necessary, to take greater responsibility for the network of which we are a part. From my point of view, it is very significant that authors such as Haraway and Barad, whose influence and popularity are ever-growing and who have been promoters of some of the most radical and timely visions of our relationship with technology, are not only philosophers, but also women and scientists. Their scientific experience in the field is evident in the way in which they treat science and technology not as mere theoretical expedients, but as real interlocutors in the elaboration of their own thought. In their work the countless configurations that matter can enter into, and its intrinsic intelligence and vitality, become a starting point for radically rethinking our position in the world.

---

1. S. Freud. 'New Introductory Lectures on Psychoanalysis. Lecture 33: Femininity', in J. Strachey (ed.), *The Standard Edition of the Complete Psychological Works of Sigmund Freud* (London: The Hogarth Press and the Institute of Psycho-Analysis, 24 vols, 1943–1974), vol. 22, 112–135: 132.
2. S. Plant, 'The Future Looms: Weaving Women and Cybernetics', *Body and Society* 1:3–4 (1995). In this text, Plant refers to the influence of the invention of the Jacquard loom on the development of the first computational machines, in particular the Analytical Engine designed by Ada Lovelace and Charles Babbage in the 1840s.
3. Irigaray develops this critique in the series of essays *Marine Lover of Friedrich Nietzsche*, tr. G.C. Gill (New York: Columbia University Press,

1991), *Elemental Passions*, tr. J. Collie and J. Still (London: Routledge, 1999), and *The Forgetting of Air in Martin Heidegger*, tr. M.B. Mader (Austin, TX: University of Texas Press, 1999), in which she argues that the forgetfulness of fluid lies at the basis of Western metaphysics. For a detailed exposition of Irigaray's thinking on physics see J. Bardsley, 'Fluid Histories: Luce Irigaray, Michel Serres and the Ages of Water', *philoSOPHIA* 8:2 (2018), 13–38.

4. D. Haraway, 'A Cyborg Manifesto: Science, Technology, and Socialist-Feminism in the Late Twentieth Century', in *Simians, Cyborgs and Women: The Reinvention of Nature* (New York; Routledge, 1991), 149–81: 181.

5. Ibid., 178.

6. Ibid., 176.

7. K. Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham, NC and London: Duke University Press, 2007).

8. Ibid., 210

9. Ibid., 379.

10. J. Bennett, *Vibrant Matter: A Political Ecology of Things* (Durham, NC and London: Duke University Press, 2010), 116.

11. Ibid., 112.

Ariadne's Thread

Fifteenth-century engraving of the labyrinth and the story of Theseus and Ariadne.

It is undeniable that, from the moment we started using technology—that is, probably long before we became human—we entered into a labyrinth whose complexity becomes greater and greater the deeper we reach. I like to imagine the path we have walked together in these pages as a passage through some corridor within this labyrinth: not a linear tale of progress, but a winding road full of surprises, blind alleys, mistakes, and unexpected discoveries. After all, no science, let alone a young and applied science such as materials science or nanotechnology, has a simple story to tell; often, those who decide to write about science are forced to choose what to include and what to exclude, finding themselves spinning a yarn even when there was not one there before.

The labyrinth is populated by monsters: hybrid creatures that we produced more or less consciously in our wonderful and unexpected encounters with matter. Some of these monsters, like those I have introduced within these pages, offer us the opportunity to forge new and fruitful alliances with the matter around us, positively modifying our environment and our culture. Others, far more threatening, jeopardise the possibility of our building a future for our species.

Daedalus, the mythical architect of the labyrinth of Knossos, designed a maze so intricate and perfect that, when he was locked within its walls with his son Icarus by the tyrant Minos, he himself, although he was the creator, was unable to find his way out. Often our destiny seems to resemble that of Daedalus: technological progress has led us to produce instruments so complex and extraordinary that we risk being trapped within the labyrinth produced by their consequences. Today it is hardly possible to speak of science and technology without underlining that the climate catastrophe now devastating our planet is the direct consequence of our actions, and is the fruit of an obsolete technological paradigm, that of fossil fuel consumption, which should have been entirely replaced decades ago with alternative technological solutions. I have chosen not to focus here on a detailed description of the technologies that materials science can offer to try and help stem the climate catastrophe, but they are many: the intelligence of new materials can be placed in the service of a more sustainable future by limiting our emissions of CO^2 and radically changing the way we produce, store, and consume energy.[1]

Faced with the ever-increasing potential of our technologies, it is easy to succumb to the temptation to take up an entirely techno-optimistic position. Unfortunately, although new technologies for energy production and storage can be further disseminated and improved, their ability to really change things is inextricably linked to our cultural and political fabric. Many of the materials that promise to bring about a ‘green revolution’ contain rare elements, non-renewable resources whose extraction has a social and environmental impact potentially comparable to that of oil. The effects of the reckless use of nanotechnology are still unknown and largely uncontrollable, precisely because of the ability of nanomaterials to interact with the most intimate structures of living organisms.

In any case, it is the relationship of domination that humans have established over the surrounding environment that is unsustainable: the search for alternative energy solutions does not touch the root of the problem, which is our inability to understand ourselves as a single node in the wider network of organisms and materials with which we share our world. If the monsters described in this book had not sufficed, the close encounter with a virus which, over the course of a few months, completely upended our way of life—a hybrid object, natural but at the same time artificial, a result of the exponential anthropisation of the planet—should have been enough to convince us that it is not necessary for an organism to be equipped with a brain, nor even to be alive in the strict sense of the word, for it to be able to intertwine its destiny with our own.

Although we undoubtedly have a responsibility to improve the situation by building more sustainable materials and more environmentally friendly technologies, imagining that some new technology or the dawn of a new science will come to save us—whether we are talking about geoengineering, biotechnology or nanomaterials—is perhaps just to naively look for an easy way out from the labyrinth in which we are trapped. We know very well how Icarus's attempt to use wax wings to fly out from between the walls of his father's labyrinth ended; looking for a technological solution to lift us above the complexity of our situation may be delude us for a while that we are in control, but it risks ending in ruin. But Icarus's flight certainly has something to teach us. Our desire to transcend the network that connects us to our technologies and to the other organisms that inhabit our planet, our claim to look at the world from a privileged perspective, will not help us solve the challenges that lie ahead; on the contrary, it will precipitate us straight onto the horns of the monsters we are fleeing. The reality is that there are no simple paths, and never will be. The way out of the labyrinth will never be upwards, but always horizontally, following its twisted ways.

The young Ariadne, perhaps because she is a woman, an expert like all Greek maidens in the ancient female art of weaving, comes up with a different solution. To her beloved Theseus, who is about to plunge into the depths of the labyrinth to defeat the monster that roams its corridors, Ariadne gives a ball of thread. Perhaps a rather humble technology compared to the superior engineering of Icarus's wings or Theseus's glittering bronze sword, Ariadne's thread nonetheless harbours a subtle form of intelligence: bending and adapting to the twisted curves of the labyrinth, flowing silently in parallel to its walls, it intertwines with the mind of the human being who explores it, allowing him to remember his path. This ancient tale should remind us that the only way out of the problem of our relationship with technology is through it: the technologies that will guide us out of the labyrinth will have to be more like Ariadne's thread than Icarus's wings, perhaps more humble and less ambitious, but cunning and flexible, capable of relating to the complexity of the reality in which we live. In this journey, the intelligence of the materials we use to orient ourselves in the world must interweave inextricably with our own, like the threads of a fabric.

---

1. For an informative exhibition of how new materials can change the future of energy, I recommend Luca Beverina's essay *Futuro Materiale. Elettronica da mangiare, plastica biodegradabile, l'energia dove meno te l'aspetti* (Bologna: Il Mulino, 2020).