Through a mind darkly
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CHAPTER 7

SCIENCE AS STRUCTURED IMAGINATION

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Abstract

This chapter offers an analysis of scientific creativity based on theoretical models and experimental results of the cognitive sciences. Its core idea is that scientific creativity—like other forms of creativity—is structured and constrained by prior ontological expectations. Analogies provide scientists with a powerful epistemic tool to overcome these constraints. While current research on analogies in scientific understanding focuses on near analogies, where target and source domain are close, we argue that distant analogies—where target and source domain differ widely—are especially useful in periods of intense conceptual change. To argue this point, we discuss three case studies from the history of science: early physiologists like Harvey, early evolutionary biologists like Darwin, and recent theorists on the evolution of the human mind like Mithen.
7.1 Introduction

What mechanisms underlie scientific creativity; what enables scientists to make significant contributions to their disciplines? The quest by philosophers of science for some explanation of scientific discovery and creativity has been recently joined by cognitive scientists (e.g., Simonton, 2003). Both philosophers and cognitive scientists examine what guides the scientific process and in what ways it resembles or differs from ordinary, everyday thought (see section 1.3). As we shall see in section 7.2, experimental psychological studies suggest that creativity is not unconstrained and limitless but structured by prior assumptions (e.g., Ward, Patterson, Sfonis, Dodds, & Saunders, 2002). Given that scientists are subject to the same cognitive limitations as other people, we argue that scientific creativity is likewise structured and constrained by prior expectations. Still, the occurrence of scientific innovations (on the level of the individual scientist) or of paradigm shifts (on the level of the scientific community) clearly indicates that scientists are able to overcome these constraining factors.

Whereas the focus of recent research on scientific creativity has been on near analogies (e.g., Dunbar, 1997), we show that distant analogies play a role in the scientific creative process, especially in periods of intense conceptual change. In our view, distant analogies constitute epistemic actions, which render problems more tractable by replacing the unfamiliar conceptual space of the target domain by a more familiar and therefore more congenial source domain. We start out with a survey of structured imagination in everyday cognition, and with the role of intuitive ontologies in this. We then examine how people overcome the constraining effects of intuitive assumptions by distant analogies that apply the structure of one domain onto a different target domain. Finally, we provide three examples from the history of science to illustrate that analogies from widely diverging domains play an important role in scientific creativity.

7.2 Structured imagination

7.2.1 Creativity is structured

What cognitive processes underlie creativity? To approach this question, the cognitive psychologist Thomas Ward (1994) asked college students to
imagine extraterrestrial animals. Their creations possessed characteristic attributes of Earth animals, such as sense organs, legs and bilateral symmetry. In a follow-up study (Ward et al., 2002), participants were asked to imagine tools that might be used by a highly intelligent species of extraterrestrials, with the following two constraints: the tools are not to be operated by power sources, and the creatures are not to have arms, legs or other appendages comparable to Earth animals. Despite these limitations, most participants relied on typical tools, such as hammers, saws and wrenches that were only slightly modified to allow the creatures to wrap them around their heads or hold them in their mouths. Subsequent interviews with the subjects revealed that a large majority heavily relied on specific examples of prototypical animals and tools to guide their creative process. Ward termed this tendency to rely on existing knowledge as a guide to creativity structured imagination (Ward, 1994). This finding has been replicated in many studies, even with children as young as five years of age (Cacciari, Levorato, & Cicogna, 1997).

Creativity in more natural settings displays the same pattern of structured imagination. Religious ideas do not exhibit an unlimited cultural variability, but are constrained by prior ontological expectations. As Pascal Boyer (2002) already observed, there are no gods that only exist on Wednesdays. Religious concepts only exhibit minimal deviations from ordinary categories. Thus, gods and other supernatural agents are invariably conceptualized as having desires, emotions and intentions; they conform to a normal belief–desire psychology. What makes them exceptional is their minimal violation of category-based expectations, such as ghosts walking through walls: these are agents with a normal belief–desire psychology who violate intuitive physical expectations. Justin Barrett (e.g., Barrett & Keil, 1996; Barrett, 1998) found that religious believers (Christians and Hindus) intuitively think about their gods as if they are normal agents. In a set of ingenious experiments, Barrett and Keil (1996) showed that Christians avowedly take God to be both omniscient and omnipresent, but when having to recall stories about him, they mistakenly recall the stories in a way that indicates their belief that God has cognitive limitations shared by normal agents (e.g., not being able to attend to two events on two different places at the same time)\(^1\).

\(^1\)The idea that religious concepts are to some extent informed by our expectations of human agents (anthropomorphism) is ancient and goes back at least to the Greek pre-Socratic Xenophanes (6th century BC), who famously speculated that religious
The historian of technology George Basalla (1988) has amply demonstrated that newly invented devices are nearly always based on existing artifacts. This is why evolutionary archeologists (e.g., O’Brien & Lyman, 2000) can study the evolution of artifacts as if they were organisms, using methods that are similar to those employed by paleontologists who study the origins, gradual morphological changes and extinction of biological species. Product design works by tinkering, not by radical restructuring which is not always advantageous: the tendency of design engineers to pattern new devices after earlier solutions often leads to suboptimal designs (Jansson, Condoor, & Brock, 1993).

The discussion above shows that existing conceptual spaces constrain creativity to an important extent, but it is less clear from where these conceptual spaces originate. In chapter 6, we saw that a growing number of studies in cognitive anthropology (e.g., Boyer, 2000; Atran, 1998) and neuroscience (e.g., Caramazza & Mahon, 2003) suggest that the way humans parse the world is not arbitrary or even solely governed by external reality, but rather that our inductive inferences rely on intuitive ontologies—a limited set of category-based evolved expectations that emerge early in development and that guide our reasoning about physical, psychological and biological phenomena. These intuitive ontologies structure our concept acquisition to an important extent, and they guide inductive inferences that underlie these concepts.

7.2.2 Analogies in everyday creative thought

How do we overcome the constraints of conceptual structures while being creative? Neuropsychological research suggests that creativity does not depend on a single cognitive process or mechanism, but rather on the interaction of several cognitive processes (Vartanian & Goel, 2007). Indeed, a variety of cognitive mechanisms underlie creativity, such as analogical and metaphorical reasoning or conceptual combination. In this chapter we will focus on analogical reasoning, our ability to understand new observations or concepts by mapping the structure of existing domains onto them (Gentner, 1983), like Niels Bohr’s analogy between the structure of imagination is structured by the way we conceptualize human beings: “if cattle or lions had hands, so as to paint with their hands and produce works of art as men do, they would paint their gods and give them bodies in form like their own—horses like horses, cattle like cattle.”, 6th century BC, Fragments, retrieved from http://history.hanover.edu/texts/presoc/kenophan.html on 17 May 2010.
7.3. Intuitive ontologies and scientific reasoning

An atom (target domain) and the structure of the solar system (source domain), the well-known orbital model.

Analogies can be considered as epistemic actions: they are performed to gain insight into a problem, which turned out to be impossible through an exploration of the original conceptual space. In contrast to pragmatic actions, which are performed to alter the world because of some intended physical change (e.g., driving from home to work), epistemic actions (e.g., driving around in order to explore one’s new neighborhood after moving) are mainly performed to aid and augment cognitive processes (Kirsh, 1996). Analogies enhance our cognitive processes as they widen or alter the conceptual space in which problems are phrased.

7.3 Intuitive ontologies and scientific reasoning

7.3.1 Intelligibility

The philosopher of science Peter Dear (2006) has argued that modern science comes in two distinguishable guises: instrumentality, or usefulness, and intelligibility, or providing accounts of how “things really are.” These two components together foster a profound trust in modern science. Why is science efficient? Because it is true. How do we know that scientific beliefs are true? By virtue of their effective instrumental capacities. It is a circular argument, but perhaps not viciously so. Of these two guises, intelligibility plays an important part, because science has taken over the role of natural philosophy to account for natural phenomena not just in ways that are internally consistent, but that somehow seem right, make sense or feel intuitively true.

Henk De Regt and Dennis Dieks (2005) claim that understanding constitutes the main epistemic aim of science. They contrast science with a hypothetical oracle, whose predictions always turn out to be true. Although in this case empirical adequacy is ensured, we do not speak of a great scientific success since we cannot understand how these perfect predictions are brought about. Scientists clearly want more: they want to grasp how predictions are made, and develop a qualitative feeling for the consequences of theories in concrete situations. Indeed, in the history of science, approaches were rarely pursued on the basis of instrumental effectiveness alone. Children and laypeople sometimes resist scientific

\[\text{In chapter 5, we considered that mathematical symbols are epistemic actions too.}\]
ideas that they find unintelligible, because their evolved cognitive architecture cannot adequately deal with them (Bloom & Weisberg, 2007). For example, children have the useful belief that unsupported objects fall downward, but this makes it difficult for them to conceptualize the world as a sphere. As a result, children create hybrid models of the world that match their intuitive understanding of physical phenomena, but that also conform to the spherical view of our planet, such as a hollow sphere or a disc-shaped earth, as we saw in subsection 1.3.3 (Vosniadou, Skopeliti, & Ikospentaki, 2004).

The effects of intuitive ontologies are not restricted to children: they linger in educated adults. As we have seen, in the case of intuitive physics, even physics students continue to apply the wrong but internally consistent impetus theory to predict the outcome of physical events. For example, they erroneously predict that a ball that is being swung in a circular path will continue to fly in a circular trajectory (Liu & MacIsaac, 2005). Intuitive ontologies may also play a role in scientific understanding, as we saw in chapter 6. For example, although expert physicists provide answers to such questions in accord with Newtonian principles, even they are guided by the intuitive impetus physics under conditions where they have to make fast judgments, where conscious deliberation is impossible. In one experiment, expert physicists had to remember the location of objects “frozen” after moving along a trajectory. Afterwards, the objects vanished, and they had to recall their position. Typically, they remembered the object somewhat further along its trajectory, along a path best described by impetus physics, not Newtonian mechanics (Kozhevnikov & Hegarty, 2001). Our intuitive ontologies lead us to perceive some accounts as more intelligible and more epistemologically satisfying than others. As we saw in section 6.5, this may account for the success and persistence of past natural philosophical theories like impetus theory. Given that one of the most important aims of science is to make nature intelligible, we can expect that intuitive ontologies will continue to play a role in scientific understanding.

### 7.3.2 Analogies and scientific creativity

Case studies from the history of science and field studies of scientists at work indicate that scientific creativity draws on the same cognitive resources as everyday creativity (Simonton, 2003). Scientists often resort
to analogies. It is useful at this point to draw a distinction between near and distant analogies. A near analogy is one in which target and source come from the same or a closely related conceptual domain. In a distant analogy, target and source come from widely diverging domains. Early work on scientific creativity tended to focus on distant analogies, such as the snake analogy mentioned by August Kekulé in his discovery of the benzene ring, or Ernest Rutherford’s comparison between the structure of our solar system and that of an atom (the planetary model). Yet, upon closer scrutiny, it turned out that these analogies were not crucial in these discoveries. A fundamental difficulty of the research on historical scientific creativity is that one has to rely on retrospective accounts, written years or even decades after the discovery was made. It is only in rare instances (such as Darwin’s notebooks) that written documents provide a reflection of the creative process in progress. Despite these limitations, which apply to any examination of historical material, the use of nonsuperficial analogies is well established both in scientists at work and in laypeople (Dunbar & Blanchette, 2001). Thus it seems plausible that written records provide an (albeit incomplete) record of analogical reasoning.

Current studies suggest that scientists mainly work within the bounds of their conceptual structures. Kevin Dunbar (1997) studied creative scientific thought in action in molecular biological labs. He found that near analogies form the most important source of creative insight, such as the analogy from a well-understood virus to a lesser-understood virus to predict how it would behave in specific circumstances. In contrast, distant analogies were rare and served explanatory purposes, rather than epistemic ones. For example, one molecular biologist likened a polymerase chain reaction to the well-known image of a group of monkeys equipped with typewriters that, given enough time, will type a sentence from Hamlet. Dunbar (1997, 488) therefore concludes that “creative ideas and novel concepts arise through a series of small changes produced by a variety of cognitive mechanisms [. . .] Conceptual change, like evolutionary change, is the result of tinkering.” The central role of near analogies accords well with classical accounts of scientific discovery, which suggest that the bulk

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3Dunbar (1997) assumes that the explanatory and epistemic roles of analogies are mutually exclusive. However, this need not be the case. Peter Lipton (1991, chapter 2), for instance, regards explanation as an essential part of scientific understanding. In this sense, an analogy that is explanatory can also play a role in scientific creativity.
of scientific work takes place within the bounds of existing well-delineated conceptual structures (e.g., Kuhn, 1962; Lakatos, 1978). Scientific imagination, like everyday creativity, is structured. Most of scientific progress takes place in mental hops, rather than leaps (to use the terminology of Ward, 1998). In other words, most scientific creativity exhibits relatively little deviation from the source domain, and preserves most of its properties.

What role then do distant analogies play in scientific discovery if near analogies alone can explain scientific progress? The molecular biologists that Dunbar (1997) investigated could draw on a wealth of well-understood mechanisms and observations. But this is not the case for scientists working in new domains where near analogies are unavailable. We propose that in these instances, distant analogies can and do play a vital role. Take Johannes Kepler, who attempted to explain why planets further from the Sun moved more slowly within the then new heliocentric Copernican model. Discarding the ancient idea that planets moved fixed on heavenly spheres, he introduced the concept of *vis motrix*, a precursor of gravity. To explain this concept, he drew on an analogy with light. The source domain of optics was fruitful because optical phenomena were better understood than the solar system:

> Let us suppose then [...] that motion is dispensed by the Sun in the same proportion as light. Now the ratio in which light spreading out from a centre is weakened is stated by the opticians. For the amount of light in a small circle is the same as the amount of light or of the solar ray in the great one. Hence, as it is more concentrated in the small circle, and more thinly spread in the great one, the measure of this thinning out must be sought in the actual ratio of the circles, both for light and for the moving power (Kepler, *Mysterium cosmographicum*, 1596, cited in Gentner et al., 1997, 16).

Another example is Stanford and Iris Ovshinsky’s invention of the threshold switch (a successor to the transistor) by analogy of the human nerve cell. During the early 1950s, the Ovshinskys recognized that plasticity of the nerve cell’s membrane plays a crucial role in the neuronal basis of human learning. Based on their observations, they created a thin film of amorphous disordered material as the analogue of the cell membrane, and used this mechanical analogue to create the threshold switch. Dur-
7.4. Distant analogies as a source of creativity

In this research, the Ovshinskys ventured into a radically new domain of science, that of amorphous disordered materials, whereas other scientists working in the domain of semiconductors still focused exclusively on crystalline materials. The creative use of distant analogy in this scientific process is plausible, since Stanford Ovshinsky had a keen interest in the neurophysiology of mammals, artificial intelligence and cybernetics, and actively corresponded with scientists working in these fields (Hoddeson, 2007). These historical cases suggest that distant analogies can play a role in periods of intense conceptual change or in the invention of radically new technological devices, when scientists cannot rely on established examples to draw near analogies from.

Because analogies are epistemic actions, performed to make problems more tractable by mapping them onto existing conceptual spaces, we expect that the source domain will be more familiar than the target domain, rather than the other way around. For example, scientific knowledge on the human mind has only seriously improved during the last 50 years with the advent of the cognitive revolution, primarily driven by computer scientists, who attempted to construct a robust science of intelligent behavior and behavioral biology. The structure and functional properties of the human mind, and of animal minds in general, remain as yet rather poorly understood. In contrast, our knowledge of how rigid objects behave (mechanics) has been expanding steadily since Antiquity. Since the human mind is less understood than mechanics, we should expect that mechanical analogies for the human mind will be more fruitful in the context of scientific discovery than vice versa (see section 7.4.3).

7.4 Distant analogies as a source of creativity in the early stages of scientific concept formation

In scientific domains where formerly intuitive ontologies played an important role, distant analogies may have been of crucial importance to move away from well-trodden paths. In this section, we examine how mapping widely diverging source domains onto target domains can foster conceptual change by three case studies: William Harvey’s mechanical and weather analogies in early modern physiology, Charles Darwin’s population biology and wedge analogies in evolutionary theory, and the use of
mechanical analogies in the understanding of the evolution of the human mind by evolutionary psychologists and cognitive archeologists.

7.4.1 Early modern physiology

A first example to illustrate how distant analogies can help us overcome intuitive ontologies is the use of mechanical analogies in early modern physiology. Experimental psychological studies (e.g., Inagaki & Hatano, 2004) show that people are intuitive vitalists: they believe that vital power is taken from food and water, enabling living things to sustain themselves, grow and prevent illness. A diminishment of vital power results in poor health, illness or exhaustion. The intuitive conceptualization in terms of a continuous vital force, which can be replenished or exhausted, is well illustrated by the so-called “health bar” in computer games, such as role playing games—the agent has one continuous measure to indicate health, which can be sustained by taking food or other replenishments. Young children often explain the functions of internal organs in purely vitalistic terms, e.g., the function of the heart is to sustain the life of its owner. Regardless of their cultural background, up to the age of five, both Australian and Japanese children prefer vitalistic over mechanistic explanations of bodily functions (Morris, Taplin, & Gelman, 2000). This vitalistic stance is also found in the work of ancient physicians. Claudius Galenus of Pergamum (2nd century AD) made significant contributions to our knowledge of blood circulation by dissecting animals. He studied the movements of the heart, the action of the valves and the pulsative force of the arteries. According to Galen, there are two kinds of blood: the dark type, found in the venous system, served as nutrition of the body. The lighter type, found in the arterial system, carried blood that was abundant in vital spirits. However, he failed to describe human circulation, which involves the transit of blood from the right to the left ventricle through the lungs (Khan, Daya, & Gowda, 2005).

It was only in the early 17th century that the precise dynamics of circulation were discovered. Prior to the 16th century, internal organs were still mainly understood in vitalistic terms. Human health and disease were understood not in terms of solid organs, but in terms of fluids (humors), such as blood, gall and phlegm, and anatomical drawings were mostly concerned with showing the arteries and nerves, rather than the organs (Fig. 7.1). Only in the course of the 17th and 18th century did
physicians turn their attention to the solid parts of the body (i.e., the organs) in their understanding of health and disease (Greenblatt, 1995).

The Renaissance revival of ancient texts included treatises on mechanics, such as Vitruvius’ *De architectura* (ca. 25 B.C.E.), which contained accounts of hydraulics and water pumping engines, next to Archimedes’ seminal works on mechanics. As a result, knowledge of hydraulics expanded rapidly during the early modern period, enabling the draining of the Low Countries. This permitted cardiovascular physiologists of that time to draw from this well-understood domain to unravel circulation, at that time poorly understood. The Paduan anatomist Benedetti published a paper in 1502 on the action of the heart valves, which he likened to unidirectional sluice gates in a canal: “three valves are purposefully placed by nature like movable gates which by turns when the heart is contracted in emitting blood do not completely shut off its passage, for these valves close inward” (cited in Novell, 1990, 397). Another Paduan
anatomist, Aquapendente, compared the action of the venous valves to a
dam or a mill sluice.

One of his pupils, William Harvey, used a variety of analogies to reason
about circulation. Although his idea that the heart was like a pair of water
bellows (not a pump, as is popularly assumed) was not novel, his colorful
use of analogies, often from the domains of mechanics or physics, enabled
him to make a more precise formulation of how human blood circulated.
In his lectures to the College of Physicians, for example, he likened the
mechanism of an erection to the inflation of a glove, and the working of
lungs and thorax to a bladder within a pair of bellows. Interestingly,
the lectures are in Latin but many of these analogies are written out in
English. In one of his lecture notes he wrote “From the structure of the
heart, it is clear that the blood is constantly carried through the lungs
into the aorta as by two clackes [a kind of pump with one-way valves] of
a water bellows to rays water” (cited in Novell, 1990, 379). In De motu
cordis, first published in 1628, Harvey wondered why the ventricles and
auricle contractions in the mammalian heart are so well-adapted to each
other and responds with two mechanical analogies:

Nor is this for any other reason than it is in a piece of machin-
ery, in which, though one wheel gives motion to another, yet
all the wheels seem to move simultaneously; or in that me-
chanical contrivance which is adapted to firearms, where, the
trigger being touched, down comes the flint, strikes against
the steel, elicits a spark, which falling among the powder, it
is ignited, upon which the flame extends, enters the barrel,
causes the explosion, propels the ball, and the mark is at-
tained—all of which incidents, by reason of the celerity with
which they happen, seem to take place in the twinkling of an
eye (Harvey, 1628 [1847], 31–32).

In the preface of De motu cordis Harvey draws a microcosm–macrocosm
analogy between the weather cycle as understood by Aristotle and the
circulatory system. This analogy, Gregory (2001) argues, was more than
a simple rhetoric device; it enabled Harvey to understand the difference
between the two types of blood, venous and arterial. Whereas this dis-
tinction did not pose a problem for Galenic physicians who understood
circulation mainly in vitalistic terms, it posed a dilemma for Harvey who
had to make the constant interconversion of the two types of blood plau-
sible. From what was known about anatomy at that time, Harvey was
unable to explain this, but the Aristotelian weather cycle provided an
apt analogy. According to Aristotle, in his *Meteorologica* (ca. 340 B.C.E.,
book I), qualitative and cyclical changes from water into air and air into
water could occur by evaporation and condensation. Just as the Sun
in the macrocosm plays a causal role in this process, so does the heart
convert the blood in the microcosm by pumping it through the lungs.
This analogy permitted a closed system for circulation (whereas Galen’s
system, where the heart consumes the blood, remained open). These
analogies from mechanics and physics enabled early modern anatomists
to steer away from the intuitive vitalism that dominated early anatomical
research. The idea that complex biological systems can be represented
in simple mechanical terms was a fundamental shift in physiology, which
remains important to this day. This shows how closely related under-
standing and scientific creativity are: by using these mechanical analogies,
Harvey came to understand puzzling features of the human circulatory
system, thereby enlarging medical knowledge.

### 7.4.2 Early evolutionary biology

As we saw in subsection 6.2.1, humans across cultures believe animals
to possess a species-typical immutable “essence” that guides their behav-
ior and development. The great innovation of Charles Darwin and Alfred
Russel Wallace was to move away from this essentialist stance by adopting
population thinking, where species are not idealized classes of entities, but
groups of individuals that differ in their ability to survive and reproduce.
As Ernst Mayr (e.g., 1982, 1987) has documented in detail, population
thinking constituted an important conceptual shift in the history of biol-
ogy which allowed biologists to discern the variability to which species are
subject. How were Darwin and Wallace able to adopt this novel way of
thinking? Population thinking is an analogy that applies Malthus’ theory
of human population dynamics to organisms in general. In brief, Thomas
Malthus (1826) in his *Essay on the principle of population* reasoned that
food resources increased more slowly than population growth. Gen-
eralizing this observation to organisms, Darwin and Wallace realized that
animals and plants too have greater reproductive potential than avail-
able resources allow. As a result, organisms will compete for the same
resources, and hence heritable traits that are advantageous will spread in
the population, because their bearers will outcompete those that do not possess them. In the introduction to the *Origin of species*, Darwin (1859, 5) made his use of this analogy explicit. Likewise, in his autobiography, Wallace, co-discoverer of the principle of natural selection, stated explicitly that he would never have hit upon his theory were it not for reading Malthus ([Wallace, 1905, 240, 360]). This distant analogy has as its source domain human populations and as its target domain animal populations. The intuitive human–nonhuman distinction discussed in section 6.6 can probably explain why this analogy arose late in biological theorizing.

Prior to these authors, biologists did not notice populations but focused on individuals. Linnaeus and others made standard idealized descriptions of species of animals and plants, such as “the daisy”, “the honeybee”. It seems remarkable that taxonomists should have overlooked the individual variation within species, given that they studied dozens of specimens before making a detailed description of a given species. Yet virtually all taxonomists prior to Darwin were species essentialists and despite their expanding taxonomical knowledge, they made little conceptual progress ([Stamos, 2005]). This led pre-Darwinian taxonomists to ignore or downplay the natural variability that species exhibit, or to understand that species can evolve into new species. Our intuitive essentialism privileges the underlying hidden essence of an organism, not its outward appearance. The skillful use of distant analogies enabled Darwin and Wallace to overcome these intuitive ontological assumptions.

Darwin struggled to understand how this Malthusian population pressure could result in evolutionary change ([Millman & Smith, 1997]). At first, he found it hard to envisage how “a multiplication of little means” could bring about the great effect of evolutionary change. To get a better grasp, he used the mechanical analogy of the wedge:

One may say there is a force like a hundred thousand wedges trying to force every kind of adapted structure into the gaps in the economy of nature, or rather forming gaps by thrusting out weaker ones. The final cause of all this wedgings, must be to sort out proper structure & adapt it to change ([Darwin, 1838, 135e]).

The wedge analogy also appears in the first edition of the *Origin of Species*:
The face of Nature may be compared to a yielding surface, with ten thousand sharp wedges packed close together and driven inwards by incessant blows, sometimes one wedge being struck, and then another with greater force (Darwin, 1859, 67).

Interestingly, Darwin dropped this analogy in subsequent editions; perhaps because by then he had developed a nearer analogy, namely between natural and sexual selection. This editing process also reveals an interesting interplay between analogies as epistemic and as explanatory tools: whereas in the notebook (not intended for publication), Darwin used the wedge analogy in an epistemic context, he later adopted it as an explanatory device, which was subsequently dropped in favor of a near analogy.

### 7.4.3 The evolution of the human mind

Once the target domain becomes better understood, distant analogies lose much of their epistemic usefulness and near analogies predominate. Indeed, an analysis of historical case studies on multiple analogies in evolutionary biology (Shelley, 1999) reveals that near analogies, such as inferences from extant species to extinct ones (e.g., from ungulates to horned dinosaurs) are more common than distant analogies. As we have seen in the case of Darwin, the latter are largely restricted to the early stages of scientific creativity. Therefore, we expect that distant analogies in contemporary scientific practice are mainly restricted to areas of research that possess an as yet underexplored conceptual structure. One candidate for such a domain is the evolution of the human mind. Despite important advances in our understanding of how the human brain evolved, its evolutionary origins remain as yet poorly understood. Thus, we can expect that authors who propose models for this domain will resort to distant analogies. The evolutionary psychologists Leda Cosmides and John Tooby’s analogy of the Swiss army knife is a well-known distant analogy for human cognition that maps the artifactual onto the psychological domain:

> The mind is probably more like a Swiss army knife than an all-purpose blade: competent in so many situations because it

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4 In sexual selection, the selective pressures are performed by potential mates rather than the external environment.
has a large number of components—bottle opener, cork-screw, knife, toothpick, scissors—each of which is well designed for solving a different problem (Cosmides & Tooby, 1994a, 60).

According to them, there are sound evolutionary reasons to expect the human mind to be made up of several dedicated domain-specific cognitive systems as specialized systems are better at solving distinct problems than a single processor: “We have both cork-screws and cups because each solves a particular problem better than the other. It would be extremely difficult to open a bottle of wine with a cup or to drink from a cork-screw” (Cosmides & Tooby, 1994a, 58). It remains to be seen whether these analogies were epistemic rather than merely explanatory in nature—or if, as Lipton (2004) would have it, both. Nevertheless, although they were aware of nearer analogies, such as multiple specialized cognitive systems in birds and primates proposed by Sherry and Schacter (1987) (see subsection 3.2.1), they continued to draw analogies from the artifactual domain, such as cognitive modules like “elegant machines” (Tooby & Cosmides, 1995, xiv).

The cognitive archeologist Steven Mithen’s Prehistory of the mind (1996) provides a further illustration of the use of distant analogies for epistemic purposes in the study of the evolution of the human mind. Mithen develops two elegant analogies. One conceptualizes human evolution as a play, divided into different acts (reminiscent of Shakespeare’s analogy of human life as a play in As you like it); it is mainly explanatory and organizational in nature. As Dunbar (1997) already noted, distant analogies often serve purely explanatory purposes, and this seems to be the case here: “Six million years [the period of human evolution since the split between the human and chimpanzee lineages] is a vast span of time. In order to begin comprehend it, to grasp its salient pattern of events, it helps to think of those events as constituting a play, the drama of our past” (Mithen, 1996, 17). Accordingly, the book’s chapters are organized into four acts, beginning with a dimly lit empty stage, representing the as yet unknown last common ancestor of humans and chimpanzees, and ending with a dramatic act representing the last 100,000 years, which sees the evolution of Homo sapiens, its expansion out of Africa, the appearance of art and, finally, the emergence of agriculture.

More interesting for the present discussion is the second distant analogy Mithen develops, that of medieval church and cathedral architecture
to understand how, according to him, human cognition changed from
domain-specific to domain-general. This second analogy is much more
crucial for Mithen’s understanding, as, by his own account (1996, 61), it
played an important role in the development of his theory of human evo-
lution, which briefly stated claims that specialized domains of intuitive
knowledge (in this dissertation referred to as intuitive ontologies) merged
in the course of human evolution. Mithen uses the different phases in me-
dieval architecture, with which he is familiar, as source domain to explain
features of the evolved human mind, an unfamiliar target domain.

During my summer vacations when a student I worked on the
excavation of the medieval Benedictine Abbey of San Vin-
cenzo in Molise, Italy. I supervised the investigation of a
particularly complex building, known as the “South Church”.  
[...] We deduced that there had been five phases in all, span-
ning the first 1,000 years AD and culminating in an elaborate
multistory building housing many of the precious relics of the
Abbey. [...] When I look at the evidence about the mod-
ern mind provided by the psychologists, I am reminded of our
work at the South Church of San Vincenzo—or indeed any
modern church or cathedral (Mithen, 1996, 61).

Mithen discerns three phases in the evolution of the human mind which
closely correspond to three phases that are distinguished in the history
of church architecture. In the first phase, the mind is like a central nave
(as in the simple one-room churches in late classical and early medieval
times), without any specialized cognitive capacities. A second phase wit-
tnesses the building of multiple “chapels” of specialized cognitive capaci-
ties around this nave, in close analogy to the building of chapels in Ro-
manesque churches. These include domain-specific capacities for reason-
ing about social life, artifacts and natural history. Pursuing this distant
analogy, Mithen argues that these domains do not influence each other:

A critical design feature of these chapels is that their walls are
thick and almost impenetrable to sound from elsewhere in the
cathedral. There is no access between the chapels. In other
words, knowledge about distinct behavioral domains cannot
be combined together (Mithen, 1996, 69).

Hominids from this phase, such as Homo ergaster, cannot reason across
domains, which would explain why they did not make specialized tools,
but rather general-purpose tools such as handaxes. In other words, since the artifactual and biological domains could not communicate, these hominids could not develop specialized hunting tools. The third phase is marked by a partial demolition of the separating walls between the distinct cognitive domains, so that information from one domain can flow to others. Here, the analogy draws on the transition from Romanesque to Gothic architecture, where the thick, heavy walls between the chapels were replaced by thinner columns. The differences between the minds of the second and the third phase are analogous to those between Romanesque and the succeeding Gothic cathedrals.

In Gothic architecture sound and light emanating from different parts of the cathedral can flow freely around the building unimpeded by the thick heavy walls and low vaults one finds in Romanesque architecture. […] Similarly, in the Phase 3 mental architecture, thoughts and knowledge generated by specialized intelligences can now flow freely around the mind […] The result is an almost limitless capacity for imagination. So we should refer to these Phase 3 minds as having a ‘cognitive fluidity’ (Mithen, 1996, 71).

Cognitive fluidity is exemplified in animism (endowing inanimate objects with a belief–desire psychology), totemism (merging social and biological domains by making animals ancestors to current human groups), and anthropomorphism (endowing animals with human properties). According to Mithen, this third phase started about 60,000 BP, when we see the first material evidence for across-domain reasoning, including specialized hunting tools which reveal a cross-fertilization of natural history knowledge and technology (e.g., harpoons for specialized fish capturing), and the emergence of therianthropes in art (half-human, half-animal creatures such as the 33,000 year old “lion man” from Hohlenstein Stadel, Germany) which reveals a crosstalk between the social and biological realms. In The prehistory of the mind the medieval cathedral analogy seeks to unify two hitherto unrelated facts about human cognition in a single explanatory framework: the fact that earlier hominids did not possess specialized, standardized tools, and the propensity of cognitively modern humans to frequently cross ontological boundaries in their reasoning. In both evolutionary psychology and cognitive archeology, authors have probed the evolutionary origins of the mind using distant analogies for epistemic
purposes. Interestingly, none of these models apply analogies from psychology; rather they draw from heterogeneous domains, notably artifacts and architectural history.

7.5 Concluding reflections

We have argued that scientific creativity draws on the same cognitive resources as other types of creativity: existing conceptual structures constrain scientists in their creative process. As a consequence, scientific creativity mostly works with small incremental steps, rather than revolutionary leaps. An important class of conceptual structures are intuitive ontologies, which guide our thinking about physical, psychological and biological phenomena. As experimental studies and the history of science reveal, they sometimes impede scientific progress. To overcome these cognitive limitations, scientists can apply distant analogies in which the ontologies of source and target domains differ widely. By presenting problems in terms of a different ontological category (e.g., the phrasing of organic functions in mechanical rather than biological terms), scientists can overcome their intuitive assumptions (e.g., vitalism) and offer solutions that are not possible in the original conceptual space. This is especially useful in the early stages of scientific creativity, when intuitive ontologies still play an important part, and in poorly understood fields of inquiry.

Note that such explorations of conceptual space are not always successful: Richard Dawkins (1989) coined the term “meme” in analogy with gene as a means to study cultural transmission. However, current models of cultural evolution (e.g., Richerson & Boyd, 2005) have not taken up this notion of replicating autonomous units of culture. There has been some scholarly interest and debate about memes, as for instance collected in the volume edited by Robert Aunger (2000). However, at present, interest for memetics has dwindled, as is evident by the fact that the only scholarly journal devoted to it, Journal of Memetics—Evolutionary Models of Information Transmission has been discontinued due to a lack of quality submissions. By contrast, models of cultural evolution relying on epidemiology—another distant analogy, this time between a biological phenomenon, viz., the epidemiology of diseases and the poorly understood

Francis Heylighen, one of the editors of the journal, personal communication.
target domain of cultural evolution—have been more successful (see sub-
section 3.2.2 and section 3.4 for a discussion of this research program).