16 Creative Combination of Representations

Scientific Discovery and Technological Invention

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INTRODUCTION

Human creativity operates in many domains, including scientific discovery, technological invention, artistic imagination, and social innovation. What are the cognitive processes that produce these creative results? Are there psychological mechanisms common to such diverse products of creativity as Darwin's theory of evolution, Edison's lightbulb, van Gogh's paintings of sunflowers, and Bismarck's introduction of old-age pensions? This chapter will develop and evaluate the *combinatorial conjecture* that all creativity, including scientific discovery and technological invention, results from combinations of mental representations.

The combinatorial conjecture has been proposed or assumed by many authors, but the evidence presented for it has been restricted to a few examples (e.g., Boden, 2004; Finke, Ward, & Smith, 1992; Koestler, 1967; Mednick, 1962; Poincaré, 1921; Thagard, 1988, 1997). This chapter gives a more thorough evaluation of the conjecture by seeing whether it applies to 100 important cases of scientific discovery and to 100 important cases of technological invention. The primary result of examination of these cases is support for the combinatorial conjecture: No counterexamples were found. But the study of 200 creative episodes was interesting in other ways, and this chapter will report a collection of findings about the nature of the representations and processes used. These findings concern the role of visual and other kinds of representations and the extent to which discoveries and inventions were accidental, analogical, and observational or theoretical.

Before getting into the historical studies, I will provide a theoretical perspective on creative conceptual combination by reviewing a new neurocomputational account that provides an explanation of how neural representations can be combined. This account accommodates visual and other nonverbal kinds of representations and therefore is capable of applying to a wide range of creative episodes. I then describe the results of study 1, which looks at 100 examples of scientific discovery, and study 2, concerning 100 examples of technological invention. These large samples confirm the combinatorial conjecture, whose claim, however, is nontrivial, as I will show by considering theoretical objections to it from the extreme embodiment perspective that thinking and hence creativity are not representational and computational. I will argue that these objections are unwarranted and that the combinatorial conjecture remains highly plausible for scientific discovery and technological invention.

NEURAL THEORY OF CONCEPTUAL COMBINATION

If creativity is to be explained as a combination of mental representations, we need a rigorous scientific account of the nature of representations and the processes that combine them. Thagard and Stewart (2011) use a neurocomputational model to show how representations construed as brain processes can be combined. This section will sketch the basic assumptions of this model without attempting to give mathematical details or general justification.

From the perspective of current work in theoretical neuroscience, concepts and other representations are patterns of firing activity in neural populations (Dayan and Abbott, 2001; Eliasmith and Anderson, 2003; O'Reilly and Munakata, 2000; Thagard, 2010a). Hence conceptual combination needs to be understood as a process of putting together new patterns of firing activity from old ones. This approach has the potential of being far more flexible than previous psychological accounts of conceptual combination that have been restricted to verbal representations. There is growing evidence that concepts are neural representations that encode information in various modalities, including verbally but also encompassing the results of sensory processes such as vision (Barsalou, Simmons, Barbey, & Wilson, 2003). In contrast to the verbal and mathematical data structures that have traditionally been used in cognitive science, neural representations are adept at capturing visual and other kinds of encodings.

There are currently two main theoretical approaches in cognitive science to the problem of binding multiple representations together. The most prominent is synchrony, through which different neural representations are bound together by virtue of their temporal coordination (Hummel & Holyoak, 2003; Shastri, 1999). Thagard and Stewart (2011) follow Eliasmith (2005, forthcoming) in employing a different method called *convolution*, which is a mathematical technique for braiding structures such as waves and vectors together. Convolution was originally developed for applications to waves in electrical engineering, but Plate (2003) showed how it could be adapted to provide an account of how vectors of numbers corresponding to the firing rates of neurons could be combined into larger structures without losing crucial structural information (see Eliasmith & Thagard, 2001, for an introduction). Then Eliasmith (2005, forthcoming) showed how convolution can be performed by populations of spiking neurons. The contribution of Thagard and Stewart (2011) is to apply such mechanisms to the Aha! experience that results when combination of neural representations is sufficiently novel that it generates an emotional reaction.

Accordingly, the combinatorial conjecture can be fleshed out as follows: All creativity results from convolution-based combination of mental representations consisting of patterns of firing in neural populations. The historical studies to be described next do not serve to evaluate these neurocomputational claims, but directly address the underlying assumption that representation combination is the fundamental mechanism of creativity in various domains.

STUDY 1: SCIENTIFIC DISCOVERY

Case studies in the history, philosophy, and psychology of science have usefully looked in detail at select examples of advances in science and technology (e.g., Gorman, Tweney, Gooding, & Kincannon, 2005). However, generalizations about the nature of scientific discovery need a more systematic look at a large number of episodes. Accordingly, I conducted an analysis of the cases described in a book called *100 Greatest Science Discoveries of All Time* (Haven, 2007). The author, Kendall Haven, is a reputable science journalist with a background as a research scientist and many publications. For my purposes, there is no need to defend the claim that these are exactly the "100 greatest," only that they are undeniably a large collection of very important discoveries, from the law of the lever to the human genome. Most crucial for a serious test of the combinatorial conjecture, the examples were not chosen by me and so were not biased by motivation to confirm rather than refute it.

For each of the 100 discoveries, it was possible to identify concepts whose combination contributed to the discovery. The first example discussed by Haven is Archimedes' discovery of the principle of the lever, that the weights pushing down on each side of a lever are proportional to lengths of the board on each side of the balance point. This principle is a newly created proposition, which I take to be a mental representation analogous to a sentence. Philosophers sometimes talk of propositions as abstract meanings of sentences, but there is no reason to believe in the existence of such abstract entities, so I will employ the cognitive science idea of a proposition as a mental representation carried out by neural processes. The new proposition about levers is clearly the result of combining other mental representations in the form of concepts such as *weight*, *push*, *side*, and *proportional.* Hence Archimedes discovery of the principle of the lever and Haven's 99 other examples all confirm the combinatorial conjecture. The spreadsheet containing my analysis of the 100 is available on request.

The example that presented the biggest potential challenge to the combinatorial conjecture was the 1938 discovery in South Africa of a coelacanth, from a species that was thought to have been extinct for over 80 million years. The curator of a local museum came across a novel fish and sent it to a biologist who recognized it from fossil records. My first impression was that this discovery was a simple perceptual recognition that did not amount to the generation of any new representations. On reflection, however, it became clear that what made this discovery creative was recognition of the existence of coelacanths that are currently alive. The criteria for creativity, as suggested by Boden (2004), are that a development be novel, surprising, and important. Merely finding a coelacanth fossil would not satisfy any of these criteria, but a live specimen was indeed surprising and important. Thus the creative discovery in this case is not just the recognition of a coelacanth, but the proposition that living coelacanths currently exist. This proposition requires the combination of concepts such as *living* and *coelacanth*, and hence serves to confirm rather than refute the combinatorial conjecture. Similarly, the serendipitous discovery of penicillin might be erroneously construed as simply a matter of perception, but what made Alexander Fleming's discovery novel, surprising, and important was his more complex recognition that mold was killing bacteria, producing the key conceptual combination *bacteria-killing mold.* Serendipity and conceptual combination go together.

Note, however, that the coelacanth discovery did not require the generation of any new concepts, as the concept *coelacanth* was already familiar to evolutionary biologists. I was surprised to find that I could identify original new concepts (indicated by newly coined words) in only 60 of the 100 cases. This is probably an undercount that could be increased by more detailed study of the cases, but there still seem to be many cases where a major scientific discovery was made without introducing novel, permanent concepts. Combination of concepts into new propositions, but not permanent new concepts, include Copernicus on the earth rotating around the sun, Galileo on falling objects, and Boyle's law of gases. It is important to recognize that the combinatorial conjecture is true concerning mental representations in the form of propositions, but would be false if it were interpreted as a claim about creativity requiring the generation of new, permanent concepts.

In looking at Haven's sample of scientific discoveries, I was interested in what kinds of mental representations were used in discovery generation. Obviously, all 100 involved verbal representations that have been used to communicate them to others, but I conjectured that visual and other kinds of mental representations that encode information in nonverbal formats might also be relevant. (For a review of different kinds of mental representation, see Thagard, 2005.) Mathematical representations are a subset of verbal representations that use numbers and/or equations. There are many scientific discoveries in which mathematics was important, ranging from Archimedes' law of the lever to Einstein's generation of $E=mc^2$. I identified 46 of the 100 discoveries as involving mathematical representations, although some digging could probably increase this number. Mathematical representations were much more common in physics than in biology and medicine, where many discoveries such as the existence of cells were qualitative. For tables summarizing the results described in this section and comparing them for those of technological invention, see the next section.

What role do nonverbal representations play in scientific creativity? Visual representations akin to pictures seemed to me important in at least 41 of the discoveries, ranging from Copernicus picturing the earth going around the sun to Robert Bakker's imagining the activities of warm-blooded dinosaurs. Some of these were more obviously visual than others as seen from their pictorial presentations, for example in Andreas Vesalius's revisionary drawings of human anatomy and Robert Hooke's drawings of cells viewed through a microscope. I found only five examples, however, where nonverbal, nonvisual representations seemed to play an important role in creative thinking, although more detailed historical analysis may well turn up more. I speculate that kinesthetic representations contributed to Archimedes' discoveries about levers and buoyancy and possibly to Galileo's discoveries about falling objects. Touch seems to have been relevant to Benjamin Franklin's discoveries about lightning and electricity because he felt sparks, and to Count Rumford's ideas about heat from friction. Sound definitely contributed to Christian Doppler's thinking about shifting frequencies. Otherwise, scientific thinking seems to have operated well just with visual and verbal (including mathematical) representations. The next section reports that nonverbal representations are much more important in technological invention.

Analysis of this relatively large sample of scientific discoveries provided an opportunity to examine questions independent of the combinatorial conjecture. I was curious how many of the discoveries were based in large part on accidents, that is events that were not the result of an intentional plan of investigation. Based on Haven's brief accounts and my own knowledge of historical events, I estimated that around a quarter of the discoveries had a substantial accidental component. For example, Galileo was not looking for moons of Jupiter with his telescope, van Leeuwenhoek was not seeking microbes with his microscope, and Roentgen was very surprised to encounter X-rays. Hence serendipity is an important part of scientific discovery, but the majority of cases seem to result from intentional problem solving. For a discussion of many cases of serendipity in scientific discovery, see Roberts (1989) and Meyers (2007).

Most unintended discoveries are observational, but serendipity can also be a feature of theoretical research. Heisenberg's uncertainty principle was an unanticipated consequence of his mathematical explorations, and Lorenz was surprised to find large outcomes from tiny changes in the starting conditions of his computational model of atmospheric storms.

Analogy has often been recognized as an important creative cognitive process, and many important examples have been identified (Holyoak & Thagard, 1995, Chapter 8). I found a significant analogical component in 14 of Haven's samples, with many cases that have not been analyzed in the philosophical or psychological literatures on analogy. It is quite possible that more examples of analogy could be found through more detailed historical analysis of the cases, but I doubt that would change the conclusion that analogy is an important but by no means exclusive mechanism for scientific creativity. Table 16.1 summarizes 14 cases of analogical discovery, noting the source analog that generated ideas about the target domain leading to a discovery. Table 16.1 also indicates the representational modalities used in addition to the ubiquitous verbal one. It is interesting that visual representations seem to be important in a greater proportion of analogical discoveries (11/14) than in discoveries in general (41/100).

Dunbar (1995) distinguished between *local* analogies that operate within a single domain and *long-distance* analogies that cross domains. All but two of the important analogical discoveries are long-distance, requiring a major mental leap across domains. Particularly interesting are three cases, indicated with an asterisk in "long,*" where the analogy served to unite previously disparate domains. Before Newton, projectile and

Table 16.1 Scientific discoveries based on analogy. See text for explanation of the asterisk in "long*"

DISCOVERY	*TARGET*	*SOURCE*	*MODALITY*	*DISTANCE*
Living cells	Living cells	Monk cells	Visual	Long
Gravity	Planetary motion	Projectile motion	Visual, mathematical, kinesthetic	Long*
Fossils	Sharks teeth	Stone teeth	Visual	Long
Life	Hierarchy	Tree	Visual	Long
Lightning	Lightning	Spark	Visual, heat	Long*
Vaccination	Smallpox	Cowpox	Visual	Local
Ultraviolet light	Ultraviolet	Infrared	Mathematical	Local
Electromagnetism	Magnetism	Electricity	Visual, mathematical	Long*
Evolution	Natural selection	Malthusian competition	Mathematical	Long
Periodic table	Elements	Piano scale	Visual	Long
Relativity	Gravity	Elevator	Visual, mathematical	Long
Fault lines	Rock layers	Rubber bands	Visual	Long
Earth mantle	Earth	Egg	Visual	Long
Quantum theory	Electrons	Crystals	Mathematical	Long

planetary motion were distinct domains, but Newtonian mechanics unified them in a common physical framework. Similarly, before Franklin, sparks and lightning were different kinds of things, and before Faraday electricity and magnetism were unconnected. In these three cases, analogical thinking brought about an important kind of conceptual change in the nature of domains that were changed through new unifying theories, so that a long-distance analogy turned into a more local one.

Philosophers often debate about the relative importance of theory and observation in science, so I coded the 100 examples for whether the discoveries were primarily:

Observational, based on perception using human senses;
Instrumental, based on observations using instruments; or

Theoretical, requiring hypotheses that go beyond the results of sensory and instrumental observation.

The results are interesting, with 70 of the discoveries theoretical, 18 observational, and 12 instrumental. Examples of discoveries made with unaided observations include Davy's discovery of anesthesia, Mendel's findings about heredity, and Fleming's discovery of penicillin. Instruments important for making observations not possible with ordinary human perception include the telescope (Galileo), microscope (Pasteur), and spectograph (Hubble).

Finally, I was interested in the extent to which scientific discoveries depended on previous technological advances and the extent to which science led to subsequent advances in technology. My counts are preliminary and should be viewed only as approximate minimums to be made more precise by more thorough historical analysis, but they are nevertheless interesting. I found 37 of the discoveries as depending in important ways on technological advances. This was obviously much more than the 12 that were directly based on instrumental observations: Many of the theoretical discoveries arose from observations that required new technologies, for example, Davy's electrochemical ideas resulting from the availability of batteries. I identified 21 scientific discoveries that in turn led to technological advances, such as Franklin's discoveries about electricity enabling him to invent the lightning rod. Thorough historical research would undoubtedly generate more examples.

Thus the study of 100 examples of scientific discovery was useful for much more than just testing the combinatorial conjecture. It served to clarify the differences between generating new propositions and generating new concepts, with only the former occurring in all cases of scientific discovery. Verbal representations seem to be universal in discoveries, but are complemented in many cases by mathematical and visual ones. Other sensory representations did not seem to be very important for scientific discovery. For lack of data, I have not addressed the role of another kind of nonverbal representation that is important for human thinking—emotion (see Thagard, 2006, 2010a). I would conjecture that every one of the 100 discoveries generated a strong, positive emotional response in the discoverer, just like Archimedes' famous Eureka! moment when he discovered the principle of buoyancy. Thagard and Stewart (2011) give an account of the neural processes that might generate such treasured moments.

This study has also generated interesting data about the extent to which discovery is accidental, analogical, theoretical, observational, and dependent on instruments. These data must be viewed as highly tentative, since they are based on brief accounts of one author and background knowledge of one interpreter. I hope they will serve to stimulate further systematic research on a larger sample of scientific discoveries that are examined in much more depth. Let us now compare scientific discovery with a similar survey of cases of scientific invention.

STUDY 2: TECHNOLOGICAL INVENTION

Previous investigation based on a few examples has suggested that invention of new technologies involves the same basic set of cognitive processes of scientific discovery (Saunders and Thagard, 2005; Thagard and Croft, 1999). Both invention and discovery require basic cognitive processes such as problem solving, analogical inference, and concept generation. But a study of a large number of inventions also turned up some interesting cognitive differences.

For my sample of inventions, I used *100 Greatest Inventions of All Time* by an experienced nonfiction writer, Tom Philbin (2003). As with my discovery sample, the "greatest" assertion should not be taken too seriously, but there is no question that Philbin identified many very important inventions, ranging from the wheel (#1) to the video recorder (#100). Unlike Haven, Philbin ranks the creations 1–100 in order of importance, but it would be hard to defend his entire ordering. A few examples appear on both lists: anesthesia, X-rays, and the transistor. As with the 100 discoveries, the analysis of 100 inventions should be viewed as highly provisional, since it may depend on both Philbin's and my idiosyncrasies. . Still, preliminary data may help to point the way to future studies that are broader and deeper.

Tables 16.2–16.5 summarize the similarities and differences found between discovery and invention. As Table 16.2 shows, all inventions, like all discoveries, involved verbal representations. This unanimity may be an artifact of the need for people (including the creators as well as commentators such as Philbin) to use language to report their discoveries to others, but inspection suggests language may well have played a role in all cases. For example, the invention of the wheel plausibly had a substantial nonverbal component owing to visual and kinesthetic representations of crucial ingredient concepts such as *log* and *rolling*, but these concepts have verbal representations as well.

It is striking in Table 16.1 that visual representations seem to be much more common in the sample of inventions than in the sample of discoveries. The reason for this difference is probably that most inventions are *things* that people can see: the wheel, lightbulb, computer, and so on. Hence people naturally have visual representations of them. For the same reason, inventions are more susceptible to other nonverbal representations such as touch, heat, kinesthesia, and sound. Mathematical representations were much less common for discoveries than for inventions, 26 rather than 46. This discrepancy may reflect the fact that Philbin had many more early examples than Haven, including 10 inventions before the Christian era in contrast to only 1 discovery that early. Cases such as the plow, sail, and bow and arrow are clearly important inventions, but the frequency of mathematical representations

Table 16.2 Kinds of representation used in scientific discovery and technological invention

	Verbal representation	*Visual representation*	*Mathematical representation*	*Other kind of representation*
Scientific discovery	100	41	46	5
Technological invention	100	87	26	48

Table 16.3 Kinds of novelty in scientific discovery and technological invention

	New propositions	*New concepts*	*Accidental*	*Analogical*
Scientific discovery	100	60	26	14
Technological invention	100	100	5	12

would have increased if Philbin had included many more recent science-dependent examples.

Table 16.3 summarizes aspects of novelty in discovery versus invention. All invention, like all discovery, generates new propositions, minimally of the form: This device serves to perform that function. Unlike discoveries, many of which do not introduce new concepts, all the inventions involved the introduction of new concepts. The difference again arises from the fact that all inventions are things, and the selected kinds were clearly important enough to warrant naming. Inventions seem to have occurred much less accidentally than discoveries, 5 versus 26, since inventions are usually the result of an intentional effort to solve some identified problem. Nevertheless, there are a few interesting cases of inventions such as anesthesia and X-ray machines that arose accidentally: Davy was not looking for a way to kill pain,

Table 16.4 Analogies in technological inventions

INVENTION	*TARGET*	*SOURCE*	*MODALITY*	*DISTANCE*
Printing press	Printing	Olive press	Visual, kinesthetic	Long
Telephone	Telephone	Ear	Visual, sound	Long
Paper	Bark paper	Hemp paper	Visual, touch	Local
Airplane	Airplane	Bird	Visual	Long*
Stethoscope	Stethoscope	Wood	Sound	Long
Microscope	Microscope	Eyeglasses	Visual	Local
Braille	Braille	Previous dots	Touch	Local
Incubator	Baby incubator	Chick hatchery	Visual, heat	Long*
Cotton gin	Cotton machine	Hand movements	Visual, kinesthetic	Local
Windmill	Windmill	Sail	Visual	Long
Washing machine	Machine	Hand movements	Visual, kinesthetic	Local
Oil derrick	Oil	Gallows	Visual	Long

Table 16.5 Theory and observation in discovery and invention

	Theoretical	*Observational*	*Instrumental*
Scientific discovery	70	18	12
Technological invention	24	76	0

and Roentgen was not looking for a way to examine bones. I was struck, however, by the highly incremental nature of invention, with many new technologies being part of a whole series of improvements in attempts to accomplish some task such as building a better lightbulb. According to Philbin's descriptions, 71 of the inventions were incremental in this way, whereas the scientific discoveries seemed to involve more dramatic leaps.

It would be interesting to determine by more detailed historical examination whether these incremental examinations can be viewed as cases of analogical inference, using past inadequate inventions as source analogs to develop new, improved targets. That finding would increase dramatically the occurrence of analogies in invention, which at 12% is a bit less than the 14% for discovery. Table 16.4 displays the analogies identified for technological invention. As with discovery, analogy seems to have been an important cognitive process in invention, but is far from being universal. All the inventive analogies plausibly have a nonverbal component. There are proportionately more local analogies than I found in discovery (5/12 vs. 2/14). Two of the long-distance analogies indicated by an asterisk were originally cross-domain but redefined the nature of domains so that we can now view them as the same domain. For example, before the Wright brothers used what they knew about birds to inform airplane construction, birds and flying machines were different kinds of objects, but now are unified under the general theory and practice of aerodynamics.

Finally, Table 16.5 shows an interesting difference between the theoretical and observational status of discoveries and inventions. I counted 76 of the inventions as observational in that they were made using ordinary human senses, with only 24 requiring theoretical leaps beyond observation. Many of these theory-based inventions were electrical devices such as the telephone. Instruments for measuring the effects of theoretical entities were undoubtedly important in many of these inventions, but none seemed to be based just on instrumental observations without a large theoretical contribution.

Comparison of discovery and invention raises interesting questions about the relation of science to technology. I found 37 cases of scientific discoveries that depended on preceding technological developments such as the telescope and spectograph. Moreover, at least 21 of the discoveries led to new technologies such as radio and the atomic bomb. Surprisingly, looking at inventions I only identified 9 of Philbin's cases as depending on prior scientific discoveries, and only 3 as generating new scientific discoveries. Perhaps these low numbers result from Philbin's assessment of "greatest" in terms of everyday usage rather than scientific importance.

A sample of 20th-century inventions would probably display a much stronger interconnection of technology and science more in accord with the findings from Haven's 100 discoveries.

OBJECTIONS TO COMBINATION

My survey of 200 examples of scientific discovery and technological invention did not turn up any counterexamples to the combinatorial conjecture, but there are other ways in which that conjecture might turn out to be false. This section considers three: abstraction, mutation from single representations, and (most radically) creativity that does not at all rely on mental representations. I have already argued that serendipitous perception in cases such as the coelacanth and penicillin are actually cases that confirm rather than refute the combinatorial conjecture.

Welling (2007) discusses four creative processes: application of existing knowledge, analogy, combination of concepts, and abstraction. The first three of these clearly involve combinations of representations, but what about the fourth, abstraction? According to Welling (2007, p. 170):

> The mental *process* of abstraction may be defined as: the discovery of any structure, regularity, pattern or organization that is present in a number of different perceptions that can be either physical or mental in nature. From this detection results the *product* abstraction: a conceptual entity, which defines the relationship between the elements it refers to on a lower, more concrete, level of abstraction.

To illustrate abstraction, Welling uses Piaget's example of children learning the concept of *weight* by abstraction of experiences of objects that are heavy and light. He speculates that children and other learners use Gestalt principles of perceptual organization such as grouping and closure.

Without a more detailed model of how abstraction works, it is difficult to assess whether it constitutes a challenge to the combinatorial conjecture. It does seem, however, that abstraction requires the combination of perceptual representations, for example the physical, kinesthetic sensations involved in assessing an object as heavy or light. I conjecture that when children learn the abstraction *weight* they put together a combination of verbal and nonverbal representations of experiences of heavy objects and light objects. If there are any cases of abstraction that are not combinatorial in this fashion, I expect that they are not particularly creative according to Boden's criteria of being new, surprising, and valuable.

Another kind of possible counterexample to the combinatorial conjecture would be if creativity arose from a kind of mutation in a single concept, analogous to the way that mutations occur in genes. Although various authors have attempted to exploit an analogy between genetic mutation and concept generation (e.g., Dawkins, 1976), I think this analogy is feeble from a cognitive perspective (Thagard, 1988, Chapter 6). Thinking is much more structured and constrained than biological evolution. In particular, no one has ever identified an interesting case of creativity arising from a random alteration in a single concept analogous to mutation in a single gene. Conceptual combinations occur in a much more focused way in the context of problem solving and hence are a much more plausible mechanism of creativity than single-concept mutations. See the Appendix for further analysis of why discovery and invention do not result from blind variations.

My analyses and arguments in defense of the combinatorial conjecture may suggest to the reader that the claim is true but trivial, making no substantive assertion. Response to the charge of triviality can be made first by pointing to the neurocomputational theory of combination that proposes a detailed neural mechanism for combining representations using convolution (Thagard & Stewart, 2011). This theory shows that the conjecture can be fleshed out into a specific claim about the cognitive and emotional processes that underlie human creativity. Second, the nontriviality of the combinatorial conjecture is evident from serious theories that deny a theoretical role for representation altogether. If there are no mental representations, then creativity is obviously not the result of combining them.

Denial of mental representations was a hallmark of behaviorism, which dominated American psychology until the cognitive revolution of the 1950s. It has been revived in a movement espousing “radical embodied cognitive science” that draws on a combination of Heideggerian philosophy, Gibsonian psychology, and dynamic systems theory to propose an alternative to the dominant computational-representational view of thinking (see, e.g., Chemero, 2009; Clark, 1997; Dreyfus, 2007; Thompson, 2007; Warren, 2006). If radical embodiment is true, then creativity does not require combining representations at all: It can be “action-first” rather than “thought-first” (Carruthers, 2011). Then the combinatorial conjecture would be false.

These extreme embodiment claims need to be distinguished from more moderate ones made by researchers such as Gibbs (2006) and Barsalou et al. (2003), who maintain that the kinds of representations and computations performed by the brain are closely tied to bodily processes such as perception and emotion. My account of neural representation is sufficiently broad to encompass a wide range of perceptual modalities, all of which can be understood as patterns of activation in populations of neurons. The body also plays a large role in my account of emotion (Thagard, 2010a; Thagard and Aubie, 2008). Hence I am happy to endorse a *moderate* embodiment thesis that acknowledges the importance of perceptual and other physiological processes (Thagard, 2010b). This moderate thesis is fully compatible with the combinatorial conjecture as long as cognition is not mistakenly restricted to only language-like representations.

So why does cognitive science, and particularly the theory of creativity, need representations? The answer is that postulation of various kinds of representations currently provides the best available explanation of many kinds of human thinking, including perception, inference, learning, problem solving, and language use (see e.g. Anderson, 2010; Smith & Kosslyn, 2007; Thagard, 2005). Proponents of the extreme embodiment thesis have barely scratched the surface in matching the explanatory successes of the computational-representational approach. Indeed, it can be argued that even the basic problem of motor control is too complex to understand without postulating representations and computations (Thagard, 2010b; Todorov & Jordan, 2002; Wolpert & Ghahramani, 2000). Abilities such as grasping objects require building complex mental models to predict the effects of various kinds of muscular operations.

More specifically, no one has a clue how to use pure embodiment to explain creative developments in science and technology. Discoveries such as relativity theory and inventions such as the telephone require the full range of human representational capacities, from verbal and mathematical to more obviously embodied representations such as vision and sound. Humans are indeed embodied dynamic systems embedded in their environments, but our success in those environments depends heavily on our ability to represent them mentally and to perform computations on those representations. Hence the embodied aspect of much of mental cognition does not refute the combinatorial conjecture, although the claims of radical embodiment do serve to show that the conjecture is a substantive one about human creativity.

According to Arthur (2009), new technologies arise as combinations of other technologies, and he even talks about how "technologies modify themselves over their lifetime" (p. 87) and describes technology as "self-producing" (p. 170). Obviously, however, past technologies have not had the capability to actually combine or modify themselves, although in the future more intelligent machines may do so (Lipson & Pollock, 2000). Rather, new technologies from wheels to iPads have resulted from the combination of human mental *representations* of previous technologies. Technological creativity is a physical process of interaction with the world, and a social process of interaction with other people. But it is also a psychological process carried out by brains that are capable of computationally modifying representations through such mechanisms as visualization, conceptual combination, analogy, and inference in general.

CONCLUSION

The two studies in this chapter have found support for the combinatorial conjecture in 200 examples of discovery and invention, but do not address whether it holds in other domains of human creativity. It should not be too hard to apply the conjecture to social innovation, which concerns the creation of new organizations, institutions, and practices that benefit human society. Innovations such as democratic government, public education, pension plans, universal health care, and international governance have contributed greatly to the quality of human lives, and I expect to show that all of these resulted in part from the combination of representations. My guess is that social innovation will turn out to be more like technological invention than like scientific discovery, except for a reduced contribution of representations that are visual.

More difficult will be assessment of the applicability of the combinatorial conjecture to the great many examples of creativity resulting from artistic imagination, including poems, plays, novels, films, music, dance, and architecture. Examination of even a few examples from these categories will require attention to many kinds of representation beyond the verbal, such as emotion in poetry, vision in film, sound in music, and kinesthesia in dance and sculpture. I expect that scrutiny of such examples will serve not just to confirm the combinatorial conjecture but also to flesh it out with greater understanding of the kinds of representations and processes that contribute to human creativity. Also needed is a general theory of how newly generated representations are evaluated for their coherence with other representations and overall value.

Although my analysis of 200 examples has been highly provisional and needs to be supplemented by a deeper and broader study, it has helped to characterize representational aspects of creativity along such dimensions as mode of representation, role of accident and analogy, and relative contribution of theory and observation. I would like to see the development of an *Atlas of Creative Science and Technology*, which would contain not only historical descriptions of great discoveries and inventions, but also their assessment with respect to the kinds of cognitive factors identified in this chapter. Creativity is combination of representations, but there is much more to be learned about the nature of these representations and the cognitive processes that produce them.

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CHAPTER 16 APPENDIX: BLIND VARIATION

Simonton (2010, Chapter 15, this volume) has attempted to revive the idea of blind variation in creativity, but I think his mathematical analysis does not go to the heart of the matter. Here is an alternative.

Let V be the set of variants that can arise in a set of structures such as genes, mental representations, machines, and so forth. V will be very large, but not infinite, as biological and physical entities are finite. The variants can be numbered $V_1 \dots V_k$, with V_i indicating some specific variant.

Then we can define G_i as the generation of variant V_i, and U_i as the utility of V_i. I propose that a variant is *blind* if its generation is independent of its utility, that is, the probability of generation given nonzero utility is the same as the probability of its generation if it were useless:

V_i is blind iff $P(G_i/U_i > 0) = P(G_i/U_i = 0)$.

Then we can say that a process of variation is overall-blind if every variant in it is blind. Genetic mutation is overall-blind, but scientific discovery, technological invention, and other forms of human creativity are overwhelmingly not, because psychological processes of problem solving and representation generation focus thinking toward variants that are more useful than random ones.

A quantitative approach has the advantage that we can talk about degree of blindedness, which is the extent to which variants in a process are blind:

Blindedness = # of blind actual variants/# of actual variants.

My survey of 100 scientific discoveries and 100 inventions suggests that the blindedness of these processes is near 0, although the difficulty of assessing the relevant probabilities and utilities makes it hard to say. Many discoveries (but hardly any inventions) have an unintentional component, but even in these cases it seems that more useful variants are more likely to be generated than useless ones. For example, Galileo never intended to find the moons of Jupiter when he turned his new telescope on the heavens, but his interests, background knowledge, and cognitive processes made it more probable that he would generate the representation "Jupiter has moons" than some utterly useless representation such as "Rome has toes." Hence discovery is not blind, and biological evolution is a poor model for scientific discovery and other kinds of creativity.