Knowledge Creation Across Worldviews: How Metaphors Impact and Orient Group Creativity

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Abstract. Metaphors are central in organization theory for they help the creation of knowledge by altering concepts or generating new ones. Yet, despite their importance, little is known about how metaphors are used in processes of knowledge creation across worldviews. In such contexts, participants maintain their specialization, work separately, and resort to interpretable devices like metaphors to create together. With a longitudinal study of a multidisciplinary scientific project aimed at repairing broken spinal cord tissues, we show how metaphors facilitate collective knowledge creation. We contribute to the theory of knowledge creation across worldviews by showing the consequences of the diverse creative outcomes of metaphors on the orientation and stability of the collective work. Moreover, we propose how to control and predict the creative outcomes of metaphors by modifying the knowledge bases that are engaged in the creative process. We contribute to the theory on cycles of knowledge creation by showing that a metaphor can extend knowledge both horizontally and vertically, and by specifying the relationships between the knowledge created and the elements that simultaneously populate the creative cycles.

Keywords: metaphors • knowledge creation • innovation • group creativity • cognition • cross-functional teams

Introduction

The beginning of our activities was rather slow and very difficult. The initial idea was to see whether these nanotubes could reconnect neuronal tissues injured by a trauma: as in the case of an accident, a spinal cord injury. That was the idea, the final goal to reach. [However] we needed to involve a neurophysiologist, so we decided to contact one who was expert on the spinal cord. ... At the beginning I thought it was easier for them to understand, as they could assume that nanotubes were like a tiny electric wire.

—Chemist (emphasis added)

When we first met it was terrible. I couldn’t even understand what he wanted.

—Neurophysiologist (admitting that “easier” was not easy)

Many of the ambitious technologies aimed at solving the problems that afflict humans’ quality of life, such as medical devices to regain hearing or movement after major accidents, are developed by multidisciplinary groups of deeply specialized individuals. These individuals need to orient their effort toward a distant vision of what the technology should accomplish, but which does not offer clear guidance in the short term. Moreover, individuals need to understand each other and become familiar with the various pieces of knowledge and with the dependencies that emerge in their interaction. Understanding how groups sustain knowledge creation and maintain their orientation toward a long-term vision, while redirecting their creative work through the steps to reach it, is therefore critical for the development of innovative technologies.

Research in organizational knowledge creation has emphasized how language helps to create shared understanding, integrate knowledge across boundaries (Baralou and Tsoukas 2015; Bechky 2003; Bruns 2013; Carlile 2002, 2004; Dittrich et al. 2016; Harvey 2013, 2014; Majchrzak et al. 2012; Tsoukas 2009), and sustain creativity (Carlile and Rebentisch 2003, Harvey 2014, Nonaka 1994, Nonaka and Von Krogh 2009, Nonaka et al. 2006). Language is particularly relevant for organizations that live and die by creativity, inasmuch as it provides the means to represent specialized knowledge and move it across boundaries ( Böl and Tenkasi 1995, Nonaka 1994), integrate it with other specialized knowledge (Majchrzak et al. 2012, Seidel and O’Mahony 2014), and orient creative work (Harvey 2014). This applies when classic coordination mechanisms such as the organizational structure, formal planning, or routines fail.

Recently some studies have indicated that synthetic representations, of which language provides plenty, suffice to span productively across boundaries (Collins et al. 2007, Majchrzak et al. 2012), even when knowledge differences between members are deep and persistent: a situation hereafter connoted as different worldviews. One particular language trope, the...
metaphor, dwells in many creative endeavors (Dunbar 1997, Dunbar and Blanchette 2001, Thagard 2012), especially when individuals collaborate across worldviews (Knorr-Cetina 1981, Majchrzak et al. 2012, Seidel and O’Mahony 2014). We know that a metaphor has the potential to alter the direction of creative work by sparking new insights, which modify the way in which a problem is tackled (Schön 1993). When enacted, a metaphor triggers a creative process that generates or modifies a concept, which we connote as a creative cycle. Yet, most studies have limited their scope to the immediate outcome of the metaphor, neglecting their temporal and spatial consequences: their relation with other metaphors and their capacity to travel across worldviews. This gap is particularly relevant in light of recent research, which has suggested that metaphors persist within an organization (Bingham and Kahl 2013), even in latent form, and therefore may bear consequences beyond the creative cycle to which they directly contribute.

This work aims to unveil the full creative potential of metaphors. We answer the call by Tsoukas (2009, p. 953) for more research on the conditions that representations “need to have to bridge specializations, facilitate shared understanding, and thus contribute to knowledge creation” by addressing the following research questions: How do metaphors help the creation of knowledge when participants have different worldviews? And what are the conditions that enable metaphors to generate different outcomes? The answers build on the notion of knowledge as a network of concepts composed by attributes tied by verbs (see Gentner 1983, pp. 156–157) and on the recognition that metaphors, as language tropes, emerge at the intersection of knowledge and material experience (Knorr-Cetina 1981, Schön 1993). Therefore, we keep track of metaphors and the relations they establish with the concepts they contribute to create or modify, the concepts from which metaphors originate, and the elements, be they cognitive or tangible, traded across worldviews (Galison 1997). To capture the outcomes of different metaphors at the conceptual level, we draw on the types of conceptual developments specified by Tsoukas (2009): conceptual expansion, combination, and reframing.

To address metaphors’ outcomes on knowledge creation, we conducted a retrospective and longitudinal study in a scientific research setting, whereby diversely specialized scientists joined forces to solve problems caused by the interruption of neuronal tissues. They worked by combining neuronal cultures with a chemical carbon material. When they started, they were among the first groups of scientists to try such a combination, and later on they became the first group to provide a theoretical model of the interaction of the two materials, and thus pioneered a growing research field. This group of scientists was ideal for our purpose, as they spent a great deal of their time working in different laboratories, handling different materials and methods, and preserving their scientific lingos. Our findings show that they relied on representations like metaphors and images to communicate with other members and orient the joint work. This study explains how knowledge is integrated and created by using metaphors and the complex process by which metaphors create knowledge.

We contribute to the growing literature on knowledge creation across worldviews (Bartel and Garud 2009, Boland and Tenkasi 1995, Majchrzak et al. 2012, Tsoukas 2009) by delineating the characteristics that allow metaphors to represent knowledge accurately enough to provide visibility across worldviews and integrate participants’ knowledge. Moreover, we expand the literature that studies creative knowledge cycles, which has posited that prior knowledge—and sometimes coherent metaphors—constrain the path of creativity (Bingham and Kahl 2013, Carlile and Rebentisch 2003, Harvey 2014). Instead, we argue that the accumulation of knowledge through metaphors is a complex process that may extend the depth of a creative path as well as broaden its horizons by enabling recombinations. We first find that not all metaphors yield the same conceptual development. Some metaphors sediment as abstract concepts of tangible materials and can be used in different times and spaces, whereas others become frames—or root metaphors—that reorganize existing concepts. We also find that the generative power of a metaphor extends beyond its original context of use: a metaphor survives creative cycles, can be reused in subsequent phases, and nested in more complex metaphors to enable new and diverse conceptual developments. Moreover, by looking at metaphors in relation to the knowledge held by the participants of the creative cycles, we discover patterns and regularities, and predict the orientation of the creative process that otherwise looks nonlinear and hard to anticipate.

In the next sections, we review the literature on metaphors in knowledge creation across worldviews and relate metaphors to specific types of knowledge creation. We then describe the methods and present our findings by portraying metaphors that accomplished different outcomes: conceptual expansion, conceptual combination, conceptual reframing, and one that produced no significant outcome other than facilitating comprehension. Finally, we report our theoretical discussion by contrasting metaphors and their outcomes, and delineate the boundary conditions, before concluding with suggestions for future research.
Theory

Metaphors in Knowledge Creation Across Worldviews

A metaphor is a language trope that describes a concept in light of a different one. This latter concept, called the source, sheds light on particular aspects of the entity described, called the target. A metaphor is often used to highlight specific elements of a complex target. For instance, the metaphor "the organization is a machine" highlights its formal structure and the interconnection among its parts. A different source foregrounds different elements of the target: when we hear that "the organization is a brain," we discover its memory and its capacity to retrieve and elaborate upon information. When a metaphor delivers an interpretable meaning of unknown targets, it becomes instrumental for work across worldviews.

A metaphor spans across worldviews when it creates a shared mental space that overcomes the incomprehensibility of specialized lingo (Schön 1993, Tsoukas 2009) and becomes a token that populates an overlapping area, called a trading zone, which helps coordinate action across worldviews (Galison 1997, Kellogg et al. 2006). A metaphor can coordinate collective action in ambiguous situations by priming others’ perception around single interpretations clarifying roles and dependencies (Weick 1996). Moreover, a metaphor renders imaginary ideas as visible, which helps converge toward a productive synthesis (Seidel and O’Mahony 2014).

A metaphor is embedded in processes with which organizations expand their knowledge by modifying or creating new concepts (Nonaka 1994), which may "form the foundation for a new process of [creative] synthesis" Harvey (2014, p.329). Organizational processes of knowledge creation are therefore cyclical and recursive. Specifically, a metaphor concurs to augment knowledge by externalizing tacit knowledge (Nonaka 1994), and by modifying the meaning of concepts (Cornelissen 2005). As to the plurality of metaphors, two additional effects have been suggested. First, metaphors "horizontally" stretch knowledge and bring new cycles far from their origin by means of associations that "continue to relate concepts that are far apart in our mind, even relate abstract concepts to concrete ones" (Nonaka and Takeuchi 1995, p. 67). A second effect suggests instead a "combinatorial" stretch, due to the capacity of a metaphor to embed other metaphors and create a so-called complex metaphor (Cornelissen and Kafouros 2008, Lakoff 2008).

However, the conceptual space in which metaphors emerge and operate is limited by the knowledge of the individuals who engage in the creative cycles, as knowledge delimits the search space and the set of combinatorial opportunities (Carlile and Rebentisch 2003). Thus, while new knowledge is stretched far from the existing knowledge base by metaphors, it is attracted by existing knowledge. What if knowledge bases are more than one and not well connected? How, then, can metaphors help the creation of new knowledge? If we want to know how far metaphors can really lead a creative process, we need to follow metaphors, knowledge, and their relationship longitudinally. Yet, such relations have been overlooked so far, which is surprising considering the relevance of the matter. With the exception of a recent study on schema emergence (Bingham and Kahl 2013), the focus has always been on the metaphor, rather than on metaphors. We therefore enquire into the relationship between creativity, knowledge, and metaphors to find out how metaphors affect a creative process.

It is with this intent that we address the call by Tsoukas (2009, p. 953; emphasis added) to “explore what kinds of [metaphors] lead to what kinds of outcomes.” However, we first need to postulate the kinds of outcome that metaphors yield.

Creating Knowledge Through Metaphors

Drawing on the work of Tsoukas (2009), there are three major pathways for knowledge creation, and metaphors, not surprisingly, contribute to each of them.

A first route by which metaphors create knowledge is by enriching a concept with a new structure and/or new attributes, a process named conceptual expansion. Formally, a concept is made of attributes (nouns, adjectives) bound by structure (verbs or a system of verbs) (Gentner 1983). When a metaphor associates two concepts, or more precisely, selected elements of them, it facilitates the import of attributes or structure from the source into the target. The magnitude of the conceptual expansion depends on the number of elements or the degree of structure imported (Gentner 1983), e.g., from a single verb or attribute to a system of verbs. Incidentally, the source can also be enriched by the comparison. Conceptual expansion enables the import of solutions from different sources, which makes metaphors viable tools for problem solving. Dunbar (1997) reports a team of biologists who approached problems by ostensibly comparing the organisms carrying the problem to those that carry solutions. The similarity between organisms enabled biologists to import hypotheses and methods, and successfully solve problems, thus expanding the concept of the target organism with knowledge of the source one.

Conceptual expansion may extend concepts to acquire related meanings that are far from their literal ones. For example, in Italy the concept of caffe has been stretched to comprise different concepts: the coffee bean, the espresso, the coffee shop, and other caffeine-rich beverages served in it (Hofstadter and Sander 2013). The concepts stretched through
conceptual expansions may favor the diffusion of products to market and audiences inaccessible prior to the meaning modification. A stretched concept of beer includes beverages that contain no or very little alcohol, such as nonalcoholic beer and other flavored blended drinks, that reach markets that forbid a more traditional concept of beer (The Economist 2013).

When an entirely new category is produced by the association of concepts, we speak of conceptual combination. Formally, given A and B concepts, conceptual combination occurs when the association produces a single concept AB. In English, A is a modifier that alters the head B. For instance, the meanings of “red brick” and “brick red” are different, as the former identifies a specific type of brick, and the latter a shade of color. By conceptual combination, a new meaning can also be attributed to the modifier. White wine is not really white (Gärdenfors 2000, pp. 114–131).

Metaphors produce conceptual combination by associating far concepts that bring their constellations of meanings together into a blended concept (Fauconnier and Turner 1998). Initially, the metaphor yields an outcome similar to that of conceptual expansion, as it facilitates the introduction of structure and attributes from the source. However, the blended concept may precipitate into a concept that develops independently from the originating ones and ends up resembling neither of them (Fauconnier and Turner 1998), thus creating a new concept (AB) that can hardly be recognized through the original constituents (A or B). A stone lion, for instance, is neither a living mammal nor a familiar resemblance of our idea of stone. Similarly, a fusion restaurant differs from a restaurant that serves both Mediterranean and Asian dishes (Kovacs and Johnson 2014). Many of the most fundamental discoveries have benefitted from conceptual combinations: the association of sound and wave; that of electricity and magnetism, disconnected until Faraday’s contribution to science; or even the conception of the printing press as an olive press, which enabled Gutenberg to think of the stone wheel as a weight to imprint ink on pages (Thagard 2012) and paved the way for an entirely new industry.

A third avenue to generate knowledge is by reordering attributes and the structure of a specific concept in light of a different concept, an action connoted as conceptual reframing. When a metaphor triggers conceptual reframing, it is used as a model, i.e., a frame, whose structure meaningfully reorganizes relations between the attributes of the target. In this case, the metaphor is also defined as a root metaphor.3

Knowledge is a repository of frames, and frames of metaphors. Frames that originate within a worldview provide useful and comprehensible perspectives (Dunbar and Blanchette 2001), while the fate of frames that originate in different worldviews is controversial. Some scholars praise their generative potential (Hargadon and Sutton 1997, Thagard 2012), while others suggest that they can be a source of contestation for being hard to assess, understand, or simply considered not apt (Nicolini et al. 2012, Seidel and O’Mahony 2014). Frames are repositories of metaphors: the “organizational behavior” metaphor stems from the frame (or root) “organization as organism.”

Two factors mainly contribute to frame activation: experience and exposure to contextual cues that inhabit the environment. People who rely on extensive field experience often draw more accurate and faster diagnoses of ambiguous situations (Herbig et al. 2001). Contextual cues provide the backdrop against which an ambiguous concept or phenomenon is confronted (Coulson 2001, pp. 34–36). Although multiple frames are simultaneously held in our mind, they are mutually exclusive: we unconsciously prefer the frame that provides sensible meaning at the lowest possible effort (Feldman 2006, Kahneman 2011, Lakoff 2008), namely, the frame that most frequently, recently, or saliently is associated with the target concept. Consider, for example, the sentence “John put the pot inside the dishwasher.” The guiding frame that likely organizes our understanding is the everyday experience of a postcooking situation. However, had we known that “the police were coming,” we could have interpreted pot as marijuana and the putting of it into the dishwasher as an act of concealment (Coulson 2001). In this case, an additional piece of information reorders attributes and their relations according to a different frame.

Figure 1 shows the outcomes of different types of conceptual change. Concepts are represented by the closed large shapes, i.e., squares, circles, or triangles, to stress their difference. Concepts contain attributes and structure, which are respectively represented by vertices and arcs. Conceptual expansion adds elements directly from the target to the source. Conceptual combination gives origin to a concept that contains elements of the two originating concepts (Domains 1 and 2), but is recognized as diverse, i.e., it has a different shape. Through conceptual reframing, the structure of the source is used to reorganize the elements of the target.

**Research Question**

We know that any creative process “requires a combination of inherited and environmental conditions to bud and bloom and reach full development” (Nersessian 2008, p. ix), and it leaves traces along its way that can be collected in subsequent cycles (Carlile and Rebentisch 2003, Harvey 2014). Metaphors remain part of the vocabulary of the organization (Bingham and Kahl 2013), which makes them available for future creative cycles. Nevertheless, previous
studies have systematically lost track of metaphors after their immediate outcome is yielded, which has impeded an unveiling of their full creative power. If we want to discover whether, how, and to what extent metaphors are reused for future creative cycles, we need to follow longitudinally and systematically the concepts that metaphors contribute to change, which makes conceptual change our dependent variable. On the other hand, we closely analyze metaphors that trigger conceptual change as well as the situation from which they originate: the constellation of concepts, individual knowledge, and images, which are the elements that stimulate knowledge creation. Specifically, we address the following research questions: How do metaphors help the creation of knowledge when participants have different worldviews? And what are the conditions that enable metaphors to generate different outcomes?

Methods
With the aim of discovering metaphors’ creative outcomes, we adopt an exploratory theory-building approach that relies on a within-case comparison of events, which draws on a qualitative historical reconstruction of a neuroscientific research project (Eisenhardt 1989, Strauss and Corbin 1990). The project started in 2002 and still continues; however, we time bracket our analysis in the period between 2002 and 2009. Such a window was sufficient to discover four polar types of metaphors with regard to their effects on conceptual development.

The Empirical Setting
The setting was selected on the basis of three important characteristics for studies on metaphors in knowledge creation across worldviews: the continuous generative effort that characterizes basic science contexts forces participants to imagine and reorient their focus on new goals once the old ones are achieved or prove unattainable; the ill-structured problem’s solution requires a series of steps, which are barely impossible to determine upfront; and the diversity of the participants’ backgrounds makes lingo ineffective for communication. Such conditions make the orientation less likely to be determined by routines or personal interests (Kaplan 2008), while enhancing the salience of flexible representations like visuals and language.

The empirical setting is that of an ambitious and successful scientific project, carried out by a changing collection of independent research groups, that we call NEUR. The project aimed at developing a new generation of carbon-made implants to repair damaged central nervous systems. NEUR received a national grant in 2003 and two important multiyear European grants in 2006 and 2009 and stands at the frontier of several scientific disciplines such as medicine, biology, engineering, chemistry, and physics. NEUR has successfully combined different research practices—in vivo, in vitro, and in silico—and experimental cultures (Knorr-Cetina 1999). Over 60 scientists have participated in NEUR at different times and from different disciplinary perspectives. However, the project was led by two scientists—a chemist and a neurophysiologist—and to a minor extent by an electrical engineer. The main chemist, ranked among the Thomson Reuters list of “Highly Cited Researchers” in 2015, and has received numerous international accolades for his work on carbon materials; he even has a chemical reaction named after him. To a minor degree, yet at earlier stages of their careers, the neurophysiologist and the engineer have received international accolades.

The duration of the scientists’ contributions to NEUR varies significantly. Several scientists contributed for one year, a few of them were sporadically invited to
perform specific measures, while others participated in NEUR for a longer period of time but carried out tasks that were peripheral to the activities discussed in this article. Two scientists—the aforementioned chemist and neurophysiologist—participated in all phases and played a major role in defining the lines of research of the team, while the engineer developed most of the conceptual work reported here in the window between 2005 and 2009.

In a nutshell, the division of labor within NEUR was as follows. The chemist and his laboratory assistants modified the characteristics of carbon nanotubes, a process called functionalization. Nanotubes were then delivered to the neurophysiology lab, where the neurophysiologist and her assistants studied the behavior of neuronal cultures under different conditions. The neurophysiologists were also responsible for arranging nanotubes together with neurons. The engineers, instead, developed computer simulations that aimed at fitting the data collected from the neuronal cultures in the neurophysiology lab.

The Empirical Material
Observing metaphors is complicated by the necessity of separating them from the technical and informational context from which they originate (Nersessian 2008). We therefore gathered a trove of materials that allowed us to triangulate each part of the story from multiple sources, and for almost each empirical step we narrate, we collected the images, i.e., visuals, or metaphors that helped the scientists imagine it. Unlike most studies on metaphors that rely on a single type of data source (see Gibbs 2008), we integrate primary and secondary sources (Eisenhardt 1989). Our material comprises interviews with scientists, laboratory visits and direct observations, internal documents, research outputs of different kinds, the archive of PowerPoint presentations, the archive of images of the aforementioned engineer and his computer simulations codes, and the interviews covered by the press.

Among the 14 semistructured interviews with 10 scientists, 10 were formally anticipated by an email or a call, and were recorded and transcribed verbatim. Four others occurred spontaneously during the visits to the labs. Interviews were collected in two rounds: eight in 2009 and six in 2014. After the first round of interviews, it emerged that metaphors helped the scientists frame their research problem, and therefore the second round zoomed in on the role of metaphors. To elicit thick descriptions, respondents were granted confidentiality. Interviews revolved around the participant’s background, their entrance to NEUR, the phase of the project at the time in which they joined, their interaction with the other participants, their work, their advancements both within their lab and with respect to NEUR, their conception of the laboratory materials and experimental layouts, experiments and their personal role in them, and the interpretation of results and measures. We confronted interviewees with experimental images to reach more complete and accurate reconstructions and “trigger responses that might lie submerged in verbal interviewing” (Collier 1957, p. 854).

To be loyal to their original interpretations, the scientists often referred to their laboratory logs during the interviews. The laboratory log is a personal diary that contains data, measurements, images, interpretations, and intuitions. At other times we invited them to describe some of the images and measurements to which we had been given access. The interviews with the three main scientists—the chemist, neurophysiologist, and engineer—were conducted face to face by two researchers. The other interviews were conducted only by the first author via Skype to guarantee a coherent protocol (Irvine 2011), as the medium enables photoelicitation.

Two other sources of primary data were three laboratory visits that lasted between one and one and a half hours, which we, the authors, used to familiarize ourselves with scientists’ tools and techniques and understand the differences in their working environments. The first author participated in a NEUR plenary research meeting whereby partners presented and discussed their latest results and tried to understand how to integrate them and move forward. The meeting was recorded and transcribed verbatim. Spontaneous conversations with scientists followed these two phases.

To complement the primary data, we used a collection of secondary sources that included PowerPoint presentations used internally and externally, research reports due to the European granting body (whereby a few preliminary results from our side were also included), 2 doctoral academic theses and 1 masters thesis, 2 computer simulations of neural modeling, 34 academic papers, 391 images in the archive of the engineer, and the material published by the press between 2005 and 2009 that contained interviews with the three main scientists: 19 newspaper articles and 3 radio interviews that were also transcribed verbatim.

To prove the effect of conceptual expansion at the field level, we analyzed search results associated with the concept expanded on ISI Web of Knowledge. We report a summary of all data sources and their use in the analyses in Table 1.

The Data Analysis
The longitudinal nature of the study urged us to take several precautions to isolate the causes that led to conceptual changes from other factors that just co-occurred in the joint work. We triangulated the interpretation after each interview (Yin 2013), relied on information overlaps that were not disconfirmed (Miller et al. 1997), had our interpretation verified
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<th>Data source</th>
<th>Type of data</th>
<th>Analytical use</th>
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<tr>
<td>Interviews</td>
<td>Semistructured interviews (10) with eight scientists of four different</td>
<td>Reconstructing the history of the project, scientists' interpretation of facts, the development of ideas, and the dynamics between the disciplinary and the cross-disciplinary activity; detection of metaphors, detection of originating concepts</td>
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<td>laboratories: physics, chemistry, neurophysiology, and engineering Informal</td>
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<td>interviews (4) with four other scientists</td>
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<td>Transcripts: 245 pages</td>
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<td>Observations lab visits</td>
<td>Laboratory visits (3): chemistry, neurophysiology, and engineering labs</td>
<td>Gaining familiarity with each laboratory's materials, techniques, and representations; supporting our interpretation and triangulating evidence</td>
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<td>Participant observation of</td>
<td>Field notes and transcription of a plenary meeting</td>
<td>Detection of metaphors and relating them to joint and within-lab work, drawing the differences between different experimental cultures</td>
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<td>a plenary meeting</td>
<td>Transcripts: 90 pages</td>
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<td>Archival data scientific</td>
<td>Scientific articles (34): 8 articles on the chemical manipulations of carbon</td>
<td>Reconstructing the history of the project and the experimental layouts, and gaining familiarity with the concepts, their development, and the techniques used by the laboratories; detection of metaphors</td>
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<td>articles</td>
<td>structures, 8 on the physiology of neurons, and 8 on computational models of</td>
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<td>neural behavior (24 in total) published by the key authors before joining the</td>
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<td>research group; 10 joint publications in the period 2002–2009</td>
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<td>Scientific theses</td>
<td>Scientific theses (2–252 pages): a doctoral thesis in chemistry based on the</td>
<td>Providing support to data and interpretation; reconstructing the history of the project</td>
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<td>activity within the lab focused on the preparation and functionalization of</td>
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<td>carbon nanotubes documenting the work carried out in the period 2006–2009;</td>
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<td>a master's thesis documenting the activity carried out in the period 2003–2005</td>
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<tr>
<td>Images</td>
<td>Laboratory and working images (391): pictures, plots, sketches, and</td>
<td>Providing support to data and interpretation; verifying the presence of metaphoric reasoning in the sketches; giving visual and real time evidence to the reconstruction of the history of the project; elicitation of more accurate responses in the interview</td>
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<td>PowerPoint presentations</td>
<td>PowerPoint drawings that were produced and used to advance ideas and share</td>
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<td>ideas with the other research partners; visuals in PowerPoint presentations</td>
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<td>(24 images from chemistry presentations, 15 from neurophysiology, and 132</td>
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<td>from engineering)</td>
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<td>Institutional report</td>
<td>Institutional report (1–114 pages) documenting all the activities and results</td>
<td>Documenting the activity of research partners and drawing relations between them</td>
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<td>Press coverage</td>
<td>Articles in the press (18–25 pages): seven in the international press and</td>
<td>Detecting the metaphors used in the dissemination</td>
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<td>11 in the Italian press; among these, two interviews with the key scientists</td>
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<td>were included in scientific journals</td>
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<td>Press interviews</td>
<td>Press interviews (3–18 pages) about the dissemination of the research results</td>
<td>Detecting the metaphors used in the dissemination</td>
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multiple times and at different stages of our research by multiple scientists (Yin 2013), and combined interviews’ and research papers’ retrospective accounts with the rich material produced in real time (Leonard-Barton 1990).

The analysis was guided by events of conceptual change that were reverse engineered to discover what led to them. At that point, metaphors were revealed as key factors that altered the design of the experiments and ultimately changed concepts. Thus, we decided to take a closer look at metaphors that triggered conceptual change. For the identification of metaphors and source validation, we followed the suggestion by Cornelissen et al. (2008), who advocated a rigorous approach. A metaphor was identified when one concept was referred to with the vocabulary of a different concept. For example, network is a metaphor both when it refers to sets of neurons, despite the existence of the modifier neuronal that makes us accustomed to the metaphor, as well as when it refers to sets of neurons and nanotubes. In addition, we connoted as root metaphors those that embedded other metaphors within their frame (Cornelissen and Kafouros 2008, Lakoff and Johnson 2008). For instance, the metaphor of percolation stems from the root of network, as we shall see. To validate metaphors’ identification, the first author imparted a short class on metaphors to 10 undergraduate students. Five of them were asked to identify metaphors from a set of quotations, whereas the other five were asked to validate the metaphors’ source domain proposed by the authors, but also had the chance to come up with their own source domain if they disagreed with our choice. We computed Cohen’s K on the interrater agreement, which was beyond the 0.8 threshold that shows high agreement (K for identification, 0.86 groupwise; pairwise minimum, 0.81; maximum, 1; for source domain validation, K = 1).

The metaphors’ outcomes were studied by means of the conceptual combination theory (Fauconnier and Turner 1998). For our purposes, the theory is consistent with other theories of metaphors (Gentner 1983, Holyoak and Thagard 1989, Lakoff and Johnson 2008), and it was chosen because it offers a diagrammatic representation that shows attributes, verbs, and their relations (i) in source and target before the metaphor is uttered (ii) and in the concept shaped by the metaphor. By difference, we learn how concepts are modified, and the contributions of the source and target, to derive the type of conceptual development brought by each metaphor. Conceptual expansion is revealed by new attributes or augmented structure in either domain, conceptual combination blends elements of the two original domains in a new concept, while conceptual reframing rearranges the target elements according to the structure of the source.

Pictorial evidence was analyzed in relation to the experimental phases. Images in general were used by scientists not simply to understand but also to report results and had different layers of interpretation. We used them to get more detailed accounts and to comprehend their effect on metaphors. Computer simulation codes were analyzed to understand how concepts (or materials) and their interactions were modeled, which refined our interpretation.

Hereafter, we report four stories that describe the fate of four metaphors (although we will use italics to signal other metaphors to the reader). We selected metaphors that yielded creative outcomes to maximize variation and to learn from their comparison (Eisenhardt 1989, Yin 2013).

Findings

For the first years, the chemist and the neurophysiologist of NEUR grappled to understand each other as well as the requirements and materials of the other disciplines. The two scientists needed to create an intersection among disciplines and share understandings with the hope of finding a common orientation for their joint work. They did so by “trading” metaphors, microscopy images, and reading materials and giving joint lectures. As the project became successful and opened to a larger number of scientists, they were the only ones, along with an engineer who joined later, who honed the capacity to engage productively with the elements that were traded. They used metaphors to unlock the access to concepts thus far mastered only within a discipline. In Table 2, we report a selection of metaphors, their source domains, relations with traded elements, locus of use, and conceptual outcomes. In the appendix, we display the relationships between metaphors, experiments, and publications.

We now devote our attention to the metaphors that yielded different types of conceptual development and one that produced no outcome other than generating shared understanding.

A Case of Conceptual Expansion: The Metaphor of Scaffold

While most metaphors expand concepts for novices, who learn new aspects, fewer affect experts: metaphors need to create knowledge. We therefore need to focus on the latter ones. In this vignette, we describe how carbon nanotubes acquire the third dimension, namely, depth, or better yet, how the chemist discovered that he could exploit the depth of a material that was until then thought of bidimensionally. The concept of the scaffold is normally deployed in chemistry to describe a material as a platform for drug delivery. Yet, by using nanotubes as a scaffold, the concept of scaffold in chemistry gains connotations that are common to the concept of the scaffold in biological sciences. Incidentally,
<table>
<thead>
<tr>
<th>Quote</th>
<th>Metaphoric source</th>
<th>Source domain</th>
<th>Triggered by</th>
<th>Use across labs</th>
<th>Led to experiment</th>
<th>Contribution to conceptual change</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Nanotubes are like tiny electric wires connecting two neurons.”</td>
<td>Electric wires</td>
<td>Electricity</td>
<td>Exchange of images</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual combination; used also for conceptual reframing</td>
</tr>
<tr>
<td>“CNTs represent a scaffold composed of small fibers or tubes that have diameters similar to those of neural processes such as dendrites.”</td>
<td>Scaffold</td>
<td>Construction, tissue engineering, chemistry</td>
<td>Exchange of images for the neurophysiologist; conceptual inheritance for the chemist</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual expansion</td>
</tr>
<tr>
<td>“Probably only the word percolation allowed me to see the same electron microscopy images in a different way. Those nanotubes touch each other; thereby I can imagine there is an electric path between any two points in the network.”</td>
<td>Percolation</td>
<td>Physics, material science</td>
<td>Exchange of images</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual reframing</td>
</tr>
<tr>
<td>“A sort of short-cut, I simplified that much. . . . I put here a resistance, here another mega resistance, and I asked ‘what are the conditions such that these points are closer if these resistances occur?’ . . . The more the neuron is long, the more these shortcuts (are efficient), and this effect should take place.”</td>
<td>Shortcuts</td>
<td>Electricity, electrical engineering</td>
<td>Elaboration of an image</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual reframing</td>
</tr>
<tr>
<td>“The effects that the two biologists just described are related to the synaptic activity into the network, so potentiation of coupling and potentiation of the synopsis which are coupling units.”</td>
<td>Network</td>
<td>Network theory</td>
<td>Exchange of images</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual reframing</td>
</tr>
<tr>
<td>“Under this neuron, there is no carbon nanotubes, and it is one of the drawbacks, instead here there is a neuron that is laying on a carbon nanotube carpet.”</td>
<td>Carpet</td>
<td>Handcraft</td>
<td>Comparison of two images</td>
<td>Yes</td>
<td>No</td>
<td>None*</td>
</tr>
<tr>
<td>“In this meshwork of nanotubes, the idea of the electric wire is a simplification of a bidimensional geometry. Assuming the symmetries of the profile, a neuron that sits over nanotubes becomes an electric wire that sits over other electric wires.”</td>
<td>Wire sitting over wires</td>
<td>Electrical engineering</td>
<td>Exchange of images</td>
<td>Yes</td>
<td>No</td>
<td>Used for conceptual reframing</td>
</tr>
<tr>
<td>“It was really funny, because the description was that of a ball, a small ball, something, like a body, with small arms. I remember it pretty clearly; this was the first description of the neuron. Because we knew very well nanotubes, but regarding cells we were a bit ignorant, and this first description of the neuron as a small ball from which some processes stemmed, that now I identify as dendrites and axons, immediately gave us the idea of what we would have seen in the first image.”</td>
<td>Body with small arms</td>
<td>Anatomy</td>
<td>Description of an object to a novice</td>
<td>Yes</td>
<td>No</td>
<td>None*</td>
</tr>
<tr>
<td>“I imagined like a finger, very very very small (the tip of microscopy), with which you touch the surface (the material in the experimental glass), and with eyes shut, like a blind man, you try to infer the shape, the morphology of the surface, simply perceiving it by contact.”</td>
<td>Finger, blind man</td>
<td>Anatomy, mechanics</td>
<td>Description of a tool to novices</td>
<td>Yes</td>
<td>Yes</td>
<td>Conceptual reframing</td>
</tr>
<tr>
<td>“Nanotubes can behave like a transistor, therefore it can be necessary an external electric field to allow an electric path. Thus a nonlinear behavior.”</td>
<td>Transistor</td>
<td>Quantum mechanics, electrical engineering</td>
<td>Analog established in the scientific literature</td>
<td>No</td>
<td>No</td>
<td>Used for conceptual reframing</td>
</tr>
</tbody>
</table>

*The metaphor contributes to translating meaning and reaching the goal of the speaker, but yields no conceptual change.
the conceptual change produced the first joint publication in NEUR.

Because of the novelty of the project and a prior failed experiment, the chemist and the neurophysiologist needed to simplify their experiment to control for fewer unknown dependences. Carbon nanotubes, which were placed between two neuronal cultures in the prior experiment, had to be recollocated. But how? The chemist, then, relied on a concept familiar to him and devised nanotubes as a substrate for the deposition of neurons:

[H]e [the chemist] initially thought that nanotubes could be the platform which could direct the neuron’s growth. Many studies in the neuronal regeneration share this idea of scaffold . . . he had this idea because he worked with peptides and he knew he could steadily hook neurons to nanotubes which have an enormous surface. Since they are tubes, cylinders, they have a very interesting ratio of exposed surface which can be functionalized. He had this idea. (Neurophysiologist)

For the chemist, in early 2000, nanodimensional carbon structures were normally associated with scaffolds, whose primary target was to deliver drugs into specific parts of the body. Carbon nanotubes, which inherited the concept of the scaffold from their “parents,” fullerenes, were promising, for they could be engineered to deliver molecules or even genetic fragments to specific areas of the body. Ideal scaffolds for drug delivery had to be porous with a matrix-like surface to facilitate the attachment of external elements, and biocompatible, so as not to activate the host’s antibodies.

On the other hand for the neurophysiologist, who back then was the only other partner in NEUR, the meaning of the scaffold was derived from the biological sciences and had little in common with that for drug delivery had to be porous with a matrix-like surface to facilitate the attachment of external elements, and biocompatible, so as not to activate the host’s antibodies. (Neurophysiologist)

In tissue engineering, [scaffold] has a precise meaning: it is a structure that favors the growth and regeneration of tissues . . . Scaffolds of this kind, however, had not yet been deployed productively on nervous tissues. (Neurophysiologist)

Before the experiment, the concept of nanotubes shared characteristics with both the aforementioned concepts of scaffolds. With the scaffold for tissue regeneration, nanotubes shared biocompatibility, a tridimensional and porous texture for the tissues to hook, while not being biodegradable—an optional feat to allow absorption by the host. With the concept of the scaffold for drug delivery, nanotubes could be functionalized to attach and carry molecules, a process for which the chemist was renowned.

However, the deployment of nanotubes as a substrate for neurons highlighted a few dependences that required further adaptation. Keeping the focus on nanotubes, scientists developed a protocol to deposit a homogenous layer with controlled thickness to allow visual recognition of the neurons. Such work modified the concept of nanotubes by blending attributes from both domains with new features that emerged from the experimental dependences. Nanotubes remained functionalizable and porous, while their use as a three-dimensional support and full biocompatibility was reached—at least with respect to neurons, since neuronal electrical activity and survival rate showed that neurons were healthy and active when coupled with nanotubes. A newly acquired characteristic, which derived from the experimental dependency, was the controlled thickness of the layer. Functionally, the new concept of the scaffold brought together the two original verbs, preserving the function of support for the tissue regeneration, but altering that of delivery, which now targeted electricity rather than drugs.

The new concept turned out to be successful, especially in the discipline of chemistry that learnt the regenerative functions of nanocarbon scaffolds (see Table 3). The first NEUR research published in 2005 showed a boosted neuronal activity in the presence of nanotubes. According to the neurophysiologist, “[i]n the long term, our results will prompt the development of new tissue engineering strategies” (interview with the press in 2005). To continue their research, however, the scientists had to expand their knowledge bases to follow up their investigations on the causes, and reached out to computational neuroscientists and electrical engineers for help.

At that time [the neurophysiologist] had the curiosity to know what in the nanotubes enhanced the neuronal
In this vignette, we describe an example of conceptual combination triggered by the metaphor of the electric wire. The metaphor was first used by the neurophysiologist to make sense of an unknown material. It ultimately structured an abstract concept, which blended elements from the concepts of neuron and nanotube that belonged to two separate disciplinary fields: neurophysiology and chemistry, respectively.

Originally, the chemist was inspired by a third party to combine nanotubes with neurons. Knowing very little about the latter, he reached out to a neurophysiologist working in a nearby research center. She was also inspired by the intuition but lacked knowledge of nanotubes. Collaboration was stifled for over a year: they hardly understood each other and could not generate sensible ideas to integrate their materials. Had they not committed to joint research by applying for a grant, which they won, they would have probably parted ways. During this period, the scientists traded readings and images, some of which are shown in Figure 2. The concept of the scaffold that resulted from the joint work expanded the meaning of scaffold employed in chemistry, the discipline of application.

We graphically illustrate the conceptual expansion in the top section of Figure 2, where we show that the newly extended concept of the scaffold that is used in chemistry (in the bottom circle) acquires structure from the concept of the scaffold in biology (top right circle). In squares, we display additional attributes of both original concepts of scaffold.

A Case of Conceptual Combination: The Metaphor of Electric Wires

In this vignette, we describe an example of conceptual combination. Despite the metaphor’s partial and inaccurate mapping, it nonetheless succeeded in suggesting to the neurophysiologist an interpretation of nanotubes. In pristine state, nanotubes are toxic, incredibly thin, resistant to tension, elastic, and are conductive only in specific thermal conditions and determinate circumstances. As an interviewee told us, “the electric wire [metaphor] wrecks on these properties that are not clear especially in this meshwork of nanotubes.” Fortunately, the neurophysiologist was not discouraged by the inaccurate mapping, of which she presumably was only partly aware.

Beyond making familiar the unfamiliar nanotubes, the metaphor favored the recognition of similarities with a third concept: neurons. Almost immediately, it became clear that neurons were also electric wires that displayed remarkable structural and morphological similarities with nanotubes: similar length to caliber ratio, rough surface, confused spaghetti structure of their propagations, and analogous conductivity, although on different types of electrical signals.

The metaphor also helped the neurophysiologist realize how to use nanotubes in practice, as carriers of neuronal signals. To carry the neuronal signal, nanotubes had to be purified and made nondissociable in water and adhesive to glass, which were conditions dictated by the copresence of neurons and the imaged experimental layout. While the metaphor led to an unsuccessful experiment, wherein nanotubes were used to connect two neuronal tissues, the conceptual combination created a new concept of nanotubes as wires for neuronal signals. Nevertheless, the concept was temporarily abandoned.

In the middle section of Figure 2, we have illustrated the mental steps of the conceptual combination eased by the metaphor. The lateral circles describe the two input concepts: neuron and nanotube. The top circle displays the abstract idea of electric wires, also called generic space, outlined by a double line, which is a mental space that encapsulates the shared structure and maps attributes of the input concepts (Fauconnier and Turner 1998). The new concept of nanotubes, in the lower circle, combines elements of both inputs.

A Case of Conceptual Reframing: The Network Root Metaphor

In this vignette, we show how the metaphors of network and shortcut, which structured one of the most prestigious works of NEUR, are nothing short of the tip of an iceberg, whose foundations are set by several other metaphors and a series of elaborations of concepts inspired by images.

When the electrical engineer joined the project, NEUR was about to publish the work developed on the basis of the scaffold metaphor (see the section A...
**Figure 2.** Diagrams of Conceptual Developments

1. **Scaffold in chemistry**
   - **Matrix structure**
     - Three-dimensional structure
     - Functionalizable
     - Biocompatible
   - **Delivers**

2. **Scaffold in biological sciences**
   - **Porous structure**
     - Three-dimensional structure
     - Biodegradable
     - Biocompatible
   - **Supports**

3. **New scaffold in chemistry**
   - **Functionalizable**
   - **Supports**
   - **Delivers**

The expanded concept of scaffold (lower circle) incorporates the verb “supporting tissue and functional regeneration” that stems from the concept of scaffold in biological sciences.

4. **Electric signal**
   - **Conducts**

5. **Neuronal signal**
   - **Conducts**

6. **Rough surface**
   - **Small diameter/high length**
   - **Mesh structure**

7. **Nanotube**
   - **Electrons**
   - **Conducts**

8. **Neuron**
   - **Conducts**

The conceptual combination (lower circle) blends the “subject” of the concept of nanotube and the “object” of that of neuron. The new concept is built through an abstract generic space (upper circle) that maps similar elements of both inputs concepts.

9. **Homogeneous nodes**
   - **Discrete connectivity**
   - **Density of lattice > t**

10. **Fluid Lattice**
    - **Percolates**
    - **Percolation theory**

11. **Neuronal signal**
    - **Network of wires**
    - **Percolates**

12. **Network of wires**
    - **Neuronal signal**
    - **Exchanged in**

*Neurons and nanotubes are modelled into a network by means of electrical equivalent concepts such as capacitors, resistors, and transistors.*

The reframed concept (lower circle) binds the attributes of the network of wires-concept to the structure of the percolation theory. Neurons and nanotubes (right circle) are transformed into a network of wires via a metaphorical transformation denoted by the asterisk.
Case of Conceptual Expansion: The Metaphor of Scaffold. The engineer wanted to understand the interaction between nanotubes and neurons. For this phase, images were particularly relevant, as they showed the morphology of the interaction. According to the neurophysiologist, one specific sequence of microscopy images, on the right side of Figure 3, showed healthy neurons that “sank in” a layer of carbon nanotubes, whereas neurons over the experimental glass were “stiff.” Instead, the engineer noted a “more conceptual” image: he saw a network whereby different types of wires were entangled. This was a conjecture that was possible for, yet unusable by, the other scientists involved at that time in NEUR, who did not share the same mathematical background.

In this meshwork of nanotubes, the idea of the electric wire is a simplification of a bidimensional geometry. Assuming the symmetries of the profile, a neuron that sits over nanotubes becomes an electric wire that sits over other electric wires. (Engineer)

The network was a root metaphor composed of other metaphors: electric wires as nanotubes and as neurons. Yet, to use the network representation, wires were mathematically mapped by a series of other concepts already deployed to model the neuronal activity (Hodgkin and Huxley 1952): transistors, capacitors, and resistors. Furthermore, “wire over wires” also denoted that the interaction occurred in a three-dimensional space. However, the metaphor of the network did not offer a specific diagnosis, but invited the engineer to search within the set of network theories.

Probably the word percolation made me see the same electronic microscopy images in a different way: these nanotubes touch themselves. So I can think of a real electric path between any two points in this network… I am not struck by the morphological aspect, I am struck by what is invisible. The images are grey, I cannot see ions: I can only imagine them moving and maybe accumulating somewhere. (Engineer)

Percolation is a theory strongly rooted in the third dimension (depth), which helped to frame the phenomenon. The frame predicted an electrical diffusion among layers under specific density network constraints. Therefore, the frame highlighted theoretical instances that had to be materially verified.

The test of the theoretical constraints occurred through the production of new images that became the backdrop for a reorganization of conceptual elements. The neurophysiologist described a new image in which nanotubes “entered the neuronal membrane, which they penetrate and pierce, as if they were proteins… (forming) a very intimate contact.” Again, where the neurophysiologist spotted an intersection, the engineer recognized a dense network and a shortcut.

If I were a neuron extended in the space, what would the effect of sitting on a bed of nanotubes be? This seems an extravagant conjecture, but these nanotubes are not isolated wires. Therefore it is not properly the same as making a shortcut, because there could be an electric loss along the path, but… While you may predict that nanotubes boost (neurons’) activity, I can tell you: they could act like a shortcut! (Engineer)

The dense contacts among nanotubes created a large electric grid platform, the bed, in which neurons were electrically embedded: neurons were wires inside a grid.
of other wires. The neuronal membrane was touched multiple times by the grid, and the engineers thereby inferred that electricity might run across different materials and reach the same destination through the faster wire. The shortcut frame predicted that the neuronal signal would leak into the nanotubes and travel faster through them, before returning into the neuron.

In this account, we see how already existing metaphors, like wire and transistor, which were originally used for different purposes and already developed concepts, were used to map and adapt the material elements to the root metaphor of network. We also see how images suggest the spatial reorganization of concepts (wire over wire, wire in wire) that echoes specific theories within the “book of network theory” that will be used as frames. The wire metaphor that once allowed the group to combine distant concepts was now deployed by the engineer in the reframing of the concepts.

In the bottom section of Figure 2, we report the steps of conceptual reframing guided by the metaphor of percolation. The new concept (bottom circle) collects attributes that belong to the interpretation of the experimental images (far right circle) and frames them after the percolation theory (left circle). The experimental materials need a sequence of metaphoric steps to be compatible with the frame.

A Metaphor That Leads Nowhere: The Carpet Metaphor

Not all metaphors shared the same fate. Some were intensively used in communication, both within disciplinary teams and across them, but essentially remained tropes that described specific entities, without affecting how these entities were experimentally manipulated or determining what variables should be observed. Their use essentially remained that of suggestive similes, which helped to establish shared understanding quickly and speed up communication. One good example is the carpet metaphor, which was recurrently employed to characterize nanotubes in technical meetings, articles, and interviews. We counted 24 occurrences of this metaphor.

They (the chemists) worked months, if not years, to make carpets of nanotubes to put neurons on top. (Physicist)

Solutions of nanotubes were given by chemists to neurophysiologists, who developed a technique to deposit them on top of the glass coverslip and form a homogeneous layer before placing the biological tissues. Like a carpet, the morphology of a layer of nanotubes was rough and had a measurable thickness.

You would never say carpet for a layer of a peptide, substantially because it is subtle, while you can say that for this material (carbon nanotubes), because it has its thickness, and in its thickness there is much of its structure, therefore it has an impact. (Neurophysiologist)

Carpet synthetically and comprehensively represented the necessary meaning to reason in the group about hypothetical scenarios, as in the case of the engineer who wondered at a meeting, “What happens if I have normal electrodes” underneath, and the biological matrix “sits on the conductive nanotube carpet?” Or to distinguish good from bad practices quickly, such as when a biologist explained the problems she faced when developing the deposition technique: “Under this neuron there are no carbon nanotubes and this is one of the drawbacks (of this method), instead here [pointing at the image projected on the whiteboard] there is a neuron that lies on a carpet of nanotubes.”

It is remarkable that the carpet metaphor was used almost exclusively by nonchemists (only one occurrence is attributed to the chemists). This suggests that the metaphor was primarily used by disciplinary “profanes” to represent some spatial characteristic of nanotube layers, namely, their thickness.

Epilogue

At the end of 2009, the composition of participants and the direction of the project radically changed. Despite much of the activity in the previous years being finalized at modeling the electrical activity, the resonance of the scaffold metaphor in the emerging scientific field suggested its recovery for the potential in the regeneration of neuronal tissues. Thus, NEUR moved on from the “electric” path of knowledge creation as the engineer left the group and new scientists joined. The two remaining leaders—the neurophysiologist and the chemist—continued to produce images to reassemble old concepts and produce metaphors.

The concept that evolved the most—for its greatest resonance—was that of the scaffold...a really three dimensional random skeleton with pores....The third dimension of the scaffold is nothing with respect to that we, here (in the lab), call nano sponges....Looking at them (directing our attention toward an image) evokes new experiments. (Neurophysiologist)

Figure 4 displays what we have discussed so far, i.e., the cycles that created knowledge by modifying the concepts of nanotubes and neurons. By showing the relationship between the outcomes, including images, we illustrate that the creation of new knowledge cumulatively builds on old metaphors. Even the metaphor, which fell off the main path, contributes to the conceptual development by means of other creative outputs, such as images, generated within the cycle.

Discussion

Finding ways to integrate knowledge across worldviews is crucial to developing new knowledge (Tsoukas 2009). Metaphors are viable tools to work across worldviews (Majchrzak et al. 2012), as they
enrich a trading zone (Galison 1997), define goals, and orient action (Harvey 2014). Yet, their contribution to knowledge creation has not been fully theorized.

Metaphors are mainly treated as “comparison mechanisms” or association makers, whose creative power is proportional to the distance of the concepts linked (Cornelissen 2005, Oswick and Jones 2006, Oswick et al. 2002) and that facilitate a “lateral” extension of the knowledge to areas not closely related to the knowledge base (Nonaka 1994, p. 25; Nonaka and Takeuchi 1995). In contrast, studies on knowledge creation cycles posit that the knowledge base is a basin of attraction for closely related knowledge, as it affects how solutions are searched and evaluated (Carlile and Rebentisch 2003, Cohen and Levinthal 1990). Taken together, the two arguments suggest the existence of forces that pull toward opposite directions, which challenge our comprehension of the relationship between new knowledge, knowledge bases, and metaphors. Therefore, we ask how metaphors affect the creation of knowledge when participants have different worldviews. And what are the conditions that enable metaphors to produce different generative outcomes?

This work shows that the contribution of metaphors to knowledge creation is more complex than the one theorized. By longitudinally studying a creative process across worldviews, we see that metaphors help create new knowledge within as well as off the current path, in proximity of as well as beyond the knowledge bases held. Conceptual developments concurrently depend on the type of knowledge bases held by participants that actively engage in the creative cycles and on the images and metaphors that are traded within them. Moreover, we show that metaphors repeatedly help to establish the steps to reach a distant goal and direct the attention of participants across worldviews. Metaphors are the stable features in a rather unstable and chaotic series of creative cycles across worldviews in which ideas bounce among participants, and problem situations get reframed without an apparent order. In such a process, individuals need representations that render knowledge visible across worldviews. Participants trade materials, images, time, and metaphors to build a trading zone (Galison 1997), but unless they hone the capacity to reason with the concepts mastered by others (Collins et al. 2007), they fail to integrate their specialized knowledge, and time is spent apparently unproductively. Metaphors are interpretable buoys to navigate obscure conceptual spaces. Metaphors are useful to reason with unfamiliar concepts, as they do not require an overly deep engagement with knowledge across worldviews. Second, metaphors are viable representations that produce different conceptual outcomes: some combine concepts to create new ones, oth-
ers extend a concept, some organize concepts according to a frame, while the remaining ones may help comprehension. A metaphor’s creative outcome does not become exhausted in a single creative cycle, nor is it limited in space. Third, when a metaphor produces a conceptual development, it orients knowledge integration toward a shared direction. When a metaphor frames, it also provides a benchmark against which to analyze results, and scope conditions within which to operate. Fourth, individuals use available metaphors by arranging them in new concepts to make sense and extend knowledge. Last, the emergence of metaphors is guided by images and the accumulated concepts. In all, we see how metaphors, which arise from the interaction of concepts, knowledge, and images, orient the way in which an organization creates knowledge across worldviews.

In the next section, we answer the first research question and delineate how metaphors help generate different conceptual developments when participants have different worldviews.

The Conceptual Contribution of Metaphors

Why have some metaphors facilitated a conceptual combination and others a conceptual reframing? Many pieces of literature indicate that a metaphor’s generative power depends on the distance between source and target (Cornelissen 2005, Cornelissen and Durand 2014, Oswick et al. 2011, Oswick and Jones 2006, Oswick et al. 2002), but then why do two metaphors, which share source and target, produce different conceptual developments? Both the electric wire and the shortcut metaphors borrowed from the domain of electricity to contribute to the development of the concepts of nanotubes and neurons. Yet, while the former originally generated a conceptual combination, the latter produced conceptual reframing.

A first discriminant of the different outcome between the two metaphors is the amount of knowledge of the source held by the participants in the creative cycles. When the electric wire metaphor was introduced, the participants could not use their knowledge bases to theorize with the metaphor, but just make sense of a material and use it. Instead, the shortcut metaphor was brought about by an expert of the source domain who deployed the metaphor to reorganize conceptual relationships between nanotubes and neurons and model their interaction. A second important discriminant is the amount of structure imported from the source in the two different metaphors (Gentner 1983). While the electric wire metaphor imports one verb, the electric conductivity, the shortcut metaphor embeds the conductivity function of the wire metaphor in a system of other verbs, which is a theoretical model grounded in the concept of network.

In contrast, a superficial knowledge of the source domain allows a metaphoric production that draws on its most apparent characteristics, be they attributes or verbs. Nonetheless, such metaphors can still make an impact in a cross-disciplinary work. A metaphor that only maps attributes does not develop concepts but can still translate meanings across worldviews and smooth cross-boundary work by rendering unfamiliar concepts visible and foregrounding specific features. On the other hand, a metaphor that hinges on structural similarities, although on apparent ones, often has profound effects by creating conceptual combinations. When a metaphor imports structure, it also suggests new ways to use the target (as the source is used). Moreover, the imported structure shapes the development of the concept, even modifying its natural attributes. Empirically we saw that when nanotubes were conceived as electric wires, they were no longer used to carry the usual electric current, but instead ions, or the neuronal signal that originated within the biological concept of neurons. This eventually produced a new concept of nanotubes as carrier of the neuronal signal.

In sum, we propose that a superior knowledge of the source domain held by the participants of the creative cycles increases the chances of importing sets of interconnected verbs, which can be imported through metaphors that reframe the structure of the target. On the other hand, a superficial knowledge of the source domain yields metaphors that will most likely trigger conceptual combination.

We advance the following propositions: (1) In the presence of a deep knowledge of the source domain, metaphors are likely to yield conceptual reframing. (2) In the presence of exclusively superficial knowledge of the source domain, metaphors are likely to lead to conceptual combinations.

So far we have looked at the relationship between knowledge and metaphors, regardless of whether metaphors’ generative power could be exploited. With this in mind, we recall the study by Bingham and Kahl (2013), who present a case in which an organization switches between collections of metaphors organized by competing frames, although metaphors contained in the abandoned frame keep producing some effect. Yet, as they focus on the psychological processes that guide the choice of a frame, they overlook the cognitive relationship between frames and their components, which are the metaphors, as well as the rationale that guides the choice between competing frames.

In this work, we demonstrate that the generative power of a frame largely depends on the possibility to exploit it, which in turns stems from the capacity to map the target elements onto the source elements. Nevertheless, the participation of experts of a source domain in creative cycles does not suffice to activate and exploit the frame, because it can still be challenging to use. Let alone the capacity to operate
with the language of the frame, which would bring us back to the argument on knowledge, it is the presence of metaphors that translate the target elements into the language of the frame that enables participants to engage fully with the frame and extract multiple interpretations from it. In our account, had expertise of the source domain sufficed to exploit a metaphoric frame, then the neurophysiologist could have activated the network frame at any time, as she was an expert of neuronal networks. However, the frame remained latent until the engineer joined. What the engineer brought was not just his new expertise, but a repertoire of metaphoric concepts like wire, transistor, capacitors, and resistors that rendered neurons and nanotubes into the abstract elements of a network. Such concepts made neurons and nanotubes treatable in the mathematical language of the network, which made it possible to exploit the frame in multiple creative cycles. The metaphors of percolation and shortcut were consequences of such intermediate metaphors.

We then propose that (3) in the presence of metaphors that map the elements and structure of a target concept onto the abstract language of the frame, the generative power of conceptual reframing increases.

When we turn to the reasons why a metaphor yields a conceptual expansion, the literature on metaphors in knowledge creation has already identified what makes such a conceptual development possible. A concept is expanded when its structure is enhanced or new attributes are revealed. The distance between and compatibility of the meanings of the source and target are the criteria that define the scope of metaphoric conceptual expansions (Cornelissen 2005). In our account, the scaffold metaphor expands the concept of scaffold in the domain of chemistry by borrowing meaning—specifically structure—from biological sciences. Such meaning, while distant and new, is deemed compatible with the target concept. Such borrowing helps constitute a richer concept. We find that such an explanation is adequate to expound the conceptual development.

So far we have contributed to the literature on knowledge creation across worldviews by showing how participants’ knowledge bases moderate the type of conceptual development triggered by metaphors. At the same time, we have contributed to the literature on metaphors by enriching the metaphoric “production function” by revealing the effects of two new elements: the knowledge of the source domain and the presence of metaphors to translate the elements of the target in the language of the source.

The second research question asks what conditions enable metaphors to generate different outcomes. To answer this question we need to focus on the relations that metaphors establish with other metaphors and images, and with the configuration of the creative cycles, which is the co-occurrence of participants and the endowment of conceptual and material elements. We illustrate how metaphors can orient the creative process across worldviews and how the orientation can be controlled by managing the knowledge bases within the organization.

**Metaphors, Images, and Creative Cycles**

The literature on knowledge creation across worldviews has stressed that the way in which knowledge is stored defines the problem space, the search for new knowledge, and how solutions are created (Carlile and Rebentisch 2003). In cases of high novelty, flexible repositories of past solutions can help solve new problems. In this regard, solutions are efficiently carried across time and space by stories and narratives that can be modified and reassembled to fit new situations (Bartel and Garud 2009, Garud et al. 2011, Pentland and Feldman 2007). Others have found that metaphors help cross boundaries and orient collective creativity, for they allow the “convergence on a tentative, fluid representation that provides[s] a common co-creation and elaboration experience” (Majchrzak et al. 2012, p. 963; see also Seidel and O’Mahony 2014). We extend this literature by illustrating how metaphors help a group create knowledge across worldviews by encapsulating fragments of specialized knowledge into abstract representations that transcend local boundaries, and populate a shared memory of concepts that is available in time and across worldviews. Yet, despite metaphors’ availability, not all participants are capable of productively engaging with them, especially when they describe unfamiliar concepts. Nevertheless, it is sufficient that only a handful of participants be capable of using metaphors to orient work across worldviews by providing procedures and tasks to be locally executed.

By populating a memory, metaphors defy time. Our longitudinal analysis illustrates two ways in which metaphors “not only exist, but also persist” (Bingham and Kahl 2013, p. 26). After its use, a metaphor can remain latent for a number of years only to reemerge as the environmental conditions change. In the epilogue, we hinted that the scaffold metaphor was reborn like a phoenix, as the composition of the group members changed. Moreover, a metaphor can be can be embedded in creative cycles even after being temporarily abandoned. The electric wire metaphor did not disappear when the scaffold became dominant, but it remained latent until it was corroborated by other metaphors and nested into a new frame. This also demonstrates how metaphors are flexible rhetorical devices inasmuch as they can be used, combined, or nested to define new problem spaces characterized by varying degrees of complexity.

We now take a closer look at the tight relationship between metaphors and images, which are also crucial...
artifacts that help integrate knowledge across worldviews (Endrissat and Noppeney 2013, Ewenstein and Whyte 2009). We show that images are crucial to spanning worldviews through metaphors, for they exhibit properties and morphological aspects that trigger the (re)cognition of familiar patterns in unfamiliar content. Thus, particular images may activate particular metathetic associations between concepts, in lieu of others that could be suggested by different images. Moreover, for the rich contexts images provide (Meyer et al. 2013), and for the flexibility of their interpretation (Kress and Van Leeuwen 2006, Tversky 2011), images are ideal entry points for new perspectives. Images afford interpretable anchors to connect minds across worldviews and options to move the creative process forward. This may explain why images were traded far more than other abstract representations, such as mathematical formulas or computer simulations that traveled far less (or not at all) across disciplines.

With the vantage point of the configuration of the creative cycle, the process reminds us of a “chaotic” organization (Cohen et al. 1972), wherein the overall direction is a joint product of the timing in which actors participate, the concepts stored in their memory, and the images available. Different frames and perspectives brought by actors can be activated only in specific time windows, when specific configurations of the elements are simultaneously present. For example, the percolation frame could not have been activated in the absence of concepts that rendered neurons and nanotubes mathematically treatable or without the engineer who mastered the domain of the source, let alone the images that magnified the third dimension. Once the frame is activated and the cycle is over, a larger endowment of concepts and images, which comprises recent outputs, provides the set for new combinations. The presence of metaphors in the memory of participants, however, does not guarantee their use in the interpretation of a problem and the setup of its solution. As we already pointed out, metaphors’ activation and exploitation for creative purposes depend on the knowledge of participants who engage with the traded elements.

Notwithstanding the “chaos,” creative cycles are not entirely unpredictable. Every cycle is oriented toward a goal, whose stability is affected by the type of conceptual development, which in turn depends on the endowment of metaphors, images, and knowledge bases that are part of the trading zone. Conceptual combinations, which we proposed to derive from superficial knowledge of the source, are extremely productive, but generate a more erratic future path than that of a process led by metaphors that conceptually reframe a problem. Therefore, once a conceptual combination is achieved, a group may stabilize the direction of work by expanding its knowledge bases toward the domain of the metaphoric source and hiring specialists to develop a frame that may be exploited for multiple creative cycles. This pattern is followed by organizations that repeatedly break through; for instance, Pixar uses a successful frame to produce multiple films (Harvey 2014). In our case, NEUR incorporated electrical engineers to develop the metaphor of the electric wire into a frame that guided a series of creative cycles.

**Boundary Conditions**

Not all organizations are as successful as the one we studied, nor is the path to novel outcomes always so smooth. A first limitation derives from the absence of pragmatic and paradigmatic tensions among the scientists we studied (Carlile 2002, 2004), which could be a consequence of the unusual, yet not so extreme, type of organization studied (Gulati et al. 2012, Kellogg et al. 2006). One reason for low pragmatic boundaries was the leeway participants had to pursue personal or local agendas that could be carried out independently from and in addition to the joint one. Participants could therefore protect their interests by a different allocation of their effort. With regard to paradigmatic boundaries, the distance across worldviews was never wide enough to require participants to engage critically with their paradigmatic assumptions. Low pragmatic and paradigmatic boundaries may have prevented us from observing deeper and reflexive discussions that might be otherwise necessary to find solutions or compromises, or to be able to take the perspective of others (Boland and Tenkasi 1995, Tsoukas 2009).

A second limitation stems from a peculiarity of microscopy images as well as the ability of actors to work with them, which might have increased participants’ capacity to think metaphorically. Despite not all participants sharing similar experiences with reasoning through images—an engineer told us “I’ve never seen as many microscopy images in my life as in those years,” which puts him at the lower end of the spectrum of “visual expertise”—we could not classify him, nor any other, as a naïve visual reasoner. In addition, microscopy differs from photography as we know it, as microscopy images are measures that display something more than the morphology. We need to employ a metaphor to make this point clear: like infrared pictures, which show the temperature of the entities in addition to their shape, microscopy images reveal certain “functions,” which aid or even guide the identification of some structural similarities, perhaps obscuring others, with direct consequences on the emergence of specific metaphors.

A third limitation derives from the absence of contestation on the direction of the work across worldviews. We advance three reasons for such absence. The first one is related to the abovementioned low
pragmatic and paradigmatic boundaries in the setting, which might have soothed the difficulties in taking the perspective of others. A second reason is the high success rate of the conceptual change produced by the observed metaphors that presumably increased participants’ trust in the creative process. The scientists were “lucky” to choose metaphors that successfully directed their work, in spite of the many potential unknown dependencies that could have manifested in the cross-functional work. The last reason is the “tunnel vision” that is activated by metaphors when they are deemed as viable solutions: a point also suggested by Gick and Holyoak (1980) in their problem-solving experiments.

However, we believe that these limitations to the generalizability of results are also a strength of the study, as they allowed us to deepen our knowledge about metaphors and how they facilitate conceptual change.

Conclusion
This study illustrates how metaphors help a multidisciplinary group create knowledge and orient their work toward a distant goal, in spite of profound knowledge and normative differences that persist among members, a situation connoted as different worldviews. Knowledge is produced when an existing concept is modified or a new one is created, in what we define as a creative cycle. We illustrate the conditions in which metaphors trigger three types of conceptual change: conceptual expansion, combination, and reframing. We extend the literature by showing that a metaphor produces effects that last longer than the creative cycle to which it directly contributes, and that it can be reused in future cycles alone or in combination with other metaphors for the same or a different type of conceptual development. For example, we describe a metaphor that originally prompted a conceptual combination, and was subsequently used for conceptual reframing. Metaphors accumulate in the memory of participants as abstract concepts that are detached from the conditions in which they originated. Yet, only participants who actively engage with the concepts that are traded across worldviews are able to use metaphors to frame new problems. We advance three propositions to delineate the conditions that lead to different types of conceptual development. The conditions relate types of conceptual changes to the knowledge bases of the individuals who engage with the traded concepts and the endowment of concepts, or they metaphoric or not. The depth of the knowledge of the source domain of the metaphor moderates the metaphoric outcome. We also propose that the presence of metaphors, which map a selection of elements of the target onto the source, augments the generative power of a conceptual reframing. With these propositions, we contribute to research on knowledge creation across worldviews and also to research on metaphors by clarifying the effects and the conditions with which metaphors help create new knowledge.

With this work, we hope to stimulate scholars to attend to metaphors for multiple creative cycles, as their creative power is not exhausted after the first generative round. We call for more research on metaphors (rather than on a metaphor) in creative endeavors in similar multidisciplinary contexts as well as more traditional ones. We encourage future research to test our propositions on the relationship between knowledge and the types of conceptual development.

We only hinted at the relationship between organizational memory and metaphors and left unexplored how the turnover of participants may affect the future use of metaphors. Moreover, it is relevant to study how the characteristics of artifacts, such as visuals, trigger certain metaphors in spite of others, thus steering the orientation of a creative process. In our study, visuals played a crucial role in activating specific metaphors, but we could not verify whether other directions for the joint work were possible at the end of each cycle. We discovered that one concept expanded by a metaphor loomed larger than others at the field level. It seemed to us that the reasons behind such a success could be linked to the resonance with existing concepts in the field, and the long wait for such a concept to be ratified. Yet, we need to know more on the conditions enabling the institutionalization of concepts. We also encourage research to look at metaphors in relation to another fundamental feature of organizing, coordination. In our case, collective work was separately carried out by teams who apparently needed little more information than the metaphoric frame to coordinate their activity. Yet, other metaphors did not trigger collective work, leaving unanswered the conditions that metaphors need to meet to contribute to cross-boundary coordination. We hope that our study will stimulate a fresh wave of research on metaphors in organizations.

Acknowledgments
This work greatly benefitted from the help of Massimo Warglien, who conducted part of the data collection and helped the authors get started. The authors acknowledge Elena Bruni, Giuseppe Delmestri, Mia Raynard, and Eva Schlindwein, whose help was invaluable to polish ideas and streamline the writing. The authors also acknowledge the anonymous reviewers, who were supportive and constructive, and the editor, Ann Majchrzak, whose direction helped tremendously. This work also benefitted from comments on earlier drafts by Eero Vaara, Pekka Palli, Richard Whittington, Victor Seidel, Anne Huff, Robert Bauer, Barbara Müller, Elango Elangovan, and Davide Nicolini. This paper would not have been possible without the support of the leading scientists of NEUR.
Appendix. The Effects of Metaphors

Figure A.1. (Color online) Metaphors in the NEUR Research Project

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Notes. Red arrows denote evolutions of metaphors into other metaphors. Blue arrows denote the metaphors that led to experiments. Green arrows show metaphors that appear in NEUR scientific articles. More recent publications, which fall after the right bracket and which are hinted at in the Epilogue, draw on the concept of the scaffold. CH, chemistry; CHt, chemist; NPH, neurophysiology; NPHt, neurophysiologist; ENG, engineering; ENGr, engineer; PHY, physics.

Endnotes

1 Gick and Holyoak (1980) show that once individuals reached a metaphorical solutions to a problem, they produced fewer alternative solutions as opposed to those who did not reach the same metaphorical description. Their result, however, did not have statistical support because of a small sample size. Similarly, Bingham and Kahl (2013) indicate that the reliance on familiar metaphors may limit the potential to exploit alternative perspectives. Taken together, the two pieces of research suggest that metaphors are mental hooks that constrain the alternatives.

2 We refer to the concept of metaphor proposed by Gentner and Markman (1997), according to which metaphors create maps between different concepts. Metaphoric maps range in a continuum between mere similarities, whereby only attributes are mapped (a pedestrian sign and a zebra), and abstractions, in which only relations are mapped, and in this former case metaphors work like models. Such a large definition includes metonyms, analogies, and similes.

3 When metaphors provide a frame, they are also called root metaphors (Lakoff 2008), models (Black 1962), or abstractions (Gentner 1983). In models and abstractions, the focus is on the identity of the relationships between the source and target, i.e., the same system of verbs, whereas the nature of attributes is disregarded.

4 The metaphors “neuronal network” and “network of nanotubes and neurons” differ for their degree of liveliness, which is shown by the common association with the modifier neuronal for the former metaphor. Such a presence demonstrates the normalization of the metaphor, which should indicate a lower creative power according to the theory of the career of metaphor (see RICOEUR 2010, Tsoukas 1991).

5 The theories slightly differ, but the Fauconnier and Turner (1998) framework is comprehensive and robust enough to explain even the types of metaphorical elaborations for which alternative theories fall short. Yet, those elaborations fall beyond the ones treated in our results (for a discussion, see Coulson 2001, pp. 168–178).

6 Our concept of borrowing differs from the metaphorical “theory borrowing” described by Oswick et al. (2011, p. 319), which mainly aims at borrowing structure from one domain to explain a phenomenon.

7 Thagard (2012) identified that metaphorical combinations gave rise to 14 of the 100 most important scientific discoveries in the history of humanity.

References


Strauss AL, Corbin JM (1990) Basics of Qualitative Research (Sage, Newbury Park, CA).

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