WIRING KNOWLEDGE DOMAINS:

METAPHORS AND KNOWLEDGE COMBINATION IN A MULTIDISCIPLINARY FIELD

ABSTRACT

In the process of combining distant domains of knowledge, metaphors play a privileged role in constructing a shared understanding and in coordinating multiple actors with different background, language and practices. Yet they are still relatively under-investigated, in particular their dynamic interplay with individual cognition and action along the knowledge creation process. Through the case study of a neuroscience research project over a eight-year period, we reconstruct the role that metaphors play in defining conceptually the object of research, interfacing and coordinating different bodies of knowledge, and informing actual practices of laboratory experimentation and technology development. We show how metaphors develop and change over the different phases of the project, responding to the new puzzles they contribute to create and to the changing composition of the network of actors involved. We offer some insight on the emergence of such metaphors and their dynamics in processes of knowledge combination.

keywords: knowledge combination, metaphor, metaphor dynamics, similarity recognition

INTRODUCTION

> “To metaphorize well implies an intuitive perception of the similarity in dissimilar” Aristotle.

Since Adam Smith (1776), it has been largely recognized that innovation is the outcome of a process of recombining different domains of knowledge. In the last couple of decades, the reincarnation of this long-standing view in the debate on innovation and knowledge combination (Kogut, & Zander, 1992; Hall, 2000) has prevailingly focused on the features of knowledge domains recombined in the innovation process, such as their degree of tacitness (Nonaka, & Takeuchi, 1995), modularity (Baldwin, & Clark 2000), technological distance (Nooteboom, Van Haverbeke, Duysters, Gilsing, & van den Oord 2007), or on firms’ characteristics facilitating knowledge transfer and combination, such as absorptive capacity (Cohen, & Levinthal, 1990; Zahra, & George 2002). Comparatively less attention has been devoted to the complex process through which such combination is achieved (Faraj, & Sproull, 2000; Leonardi, 2011). Moreover, research on innovation management has mostly focused on knowledge combination as a transfer process, comparatively neglecting the phenomenon of the modification of knowledge through recombination and the creation of a genuinely new knowledge domain.

In this paper, we join the relatively less developed thread of research focusing on the process of new knowledge generation by the combination of heterogeneous sources of knowledge. Previous research on the combination process has focused on issues such as knowledge transformation[1] (Carlile, 2002), knowledge brokerage (Hargadon, 2002; Hargadon, & Bechky, 2006; Hargadon, & Sutton, 1997; Sutton, & Hargadon, 1996) or the role of objects in coordinating and solving

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[1] As Carlile (2002: 445) defines, “transforming knowledge refers to a process of altering current knowledge creating new knowledge, and validating it within each function and collectively across functions.” This process is required when there is difference across knowledge bases, dependence as well as novelty.

boundary spanning problems (Bechky, 2003; Carlile, 2002; 2004; Hsiao, Tsai, & Lee, 2011; Levina, & Vaast, 2005).

These bodies of literature mostly highlight the social interplay needed to transform knowledge. We focus here instead on the role that language and cognition play in the process of coordinating actors with large differences in their disciplinary knowledge background and language, loci of work, practices and tools in their effort to generate genuinely new, cross-disciplinary knowledge. In particular, we focus on metaphors, a language trope whose centrality in our conceptual system has been increasingly recognized (Lakoff, & Johnson, 1979, Ortony, 1993, Gärdenfors, 2000, Gibbs, 2008). Metaphors are language expressions that open a window on the nature of human mental representations and thinking; they live in linguistic communication, but reveal important aspects of our inner mental processes. They are thus ideal lenses over the process by which actors with different systems of concepts and categories grapple to achieve a common understanding of something novel to all of them.

Metaphors are increasingly calling the attention of management scholars due to their creative role for sensemaking and directing collective change (Hill & Levenhagen 1995; Cornelissen & Clarke 2010), and as they aid actors to build new knowledge from prior experience (Dunbar 1997, 1999). Notwithstanding recent contributions on grounding understanding (Clark, 1996) in situations in which distance between domains is high and communication is unproductive (Bechky, 2003), little is known about how metaphors work as a mechanism of communication and knowledge creation across actors with diverse disciplinary backgrounds. Therefore the aim of this paper is to analyze metaphors in processes of knowledge generation across distant disciplines.

We focus on the dynamics of metaphors addressing the question of how metaphors work throughout the combination process. Our aim is to extend research on how metaphors emerge, and how they frame activities and change by bridging multiple actors and disciplines over time. First we analyze how metaphors emerge as heuristic instruments that not just cast light on novel features in a specific discipline (Black, 1979; Cornelissen, 2004), but help to mould a new cognitive domain bridging multiple input knowledge spaces (Fouconnier and Turner 1998). Secondly, we study how metaphors interact with actions (Dunbar 1997; 1999) and evolve over time in a building process of a multidisciplinary knowledge domain.

Through the analysis of the development of a nanotechnology research project over a time period of eight years, we reconstruct the role that metaphors play in defining conceptually the object of research at the project inception, interfacing and coordinating different bodies of knowledge. Moreover we focus on the metaphors dynamics. On the one hand we show metaphors' impact on researchers actions: looking at their facilitating role in the identification of intermediate adjustments and investigating how they inform actual practices of laboratory experimentation and technology development. On the other hand, we show how metaphors develop and change over the different phases of the project, responding to the new puzzles they contribute to create and to the changing composition of the network of actors involved.

In the next sections of the paper, we first develop the theoretical framework. In the method section we describe our exploratory and longitudinal fieldwork. In the following section we reconstruct the role that metaphors played in the effort of knowledge combination in the main three experiments of the project under investigation. Then we discuss the heuristic power of metaphor and cast light on the impact metaphors have on actions and the subsequent impact actions have on the life and use of metaphors. Finally, we draw conclusions and theoretical implications.

THEORETICAL BACKGROUND: A SHORT DETOUR ON METAPHORS AND KNOWLEDGE COMBINATION

Traditionally, metaphor is defined as "a figure of speech in which a word or phrase is applied to an object or action to which it is not literally applicable" (Oxford English Dictionary). It is often associated to poetical or rhetorical use of words: the figurative use is opposed to the literal one.

However, after being relegated for long time to the peripheral domain of language artifacts and rhetoric, in the last decades metaphor has come to occupy the central stage of our understanding of human thought and action. In their influential book on "Metaphors we live by", Lakoff and Johnson (1979: 4) have stated that “our ordinary conceptual system, in terms of which we both think and act, is fundamentally metaphorical in nature.”

Cognitively speaking, metaphors provide an understanding of things and events in terms of other things or events. Metaphors can structure much of our daily experience (as in the conception of time as space), but they are also fundamental in dealing with previously unexperienced situations, by projecting what we already know about a domain onto the new domain and thus shaping our understanding of it. Thus, metaphors help us to provide meaning to new experiences and objects, and they offer systematic guides to generate inferences and direct action in relatively unknown contexts. They may also offer a guide to imagine new things, by providing a way to structure relationships among elements according to the structure of the original domain of the metaphor - metaphors can be "generative" (Schoen, 1993). For example seeing a DNA strand as "two-legged" helps to imagine a piece of DNA that "walks" along another strip of DNA (Shin, & Pierce, 2004).

Of course, since metaphors are not identities, they are selective: some elements get hidden while others are emphasized. A mechanistic metaphor of organizations (Morgan, 1986) fatally hides the political side of organizing .

Metaphors, are not just conceptual, they also affect actions. We "live by" metaphors because the way we act and react is structured by the expectations and even the values which are carried by a metaphor. Conceiving a market competitor as "enemy", will favor aggressive marketing behavior (Rindova, Becerra, & Contardo, 2004).

Finally, metaphors are fundamental to share concepts and coordinate action with others. Metaphors are powerful vehicles to convey and translate to others meanings that could hardly be expressed literally (as for emotions), or that could be not understood if expressed literally (as for specialized, idiosyncratic knowledge). Metaphors have been identified as cause and driver of collectively coordinated efforts towards a goal (Dunbar, 1997; 1999) and for their power to attribute meaning to the world, recruit external aid and provide the legitimacy and familiarity to new scenarios (Cornelissen, & Clarke, 2010; Cornelissen, Holt, & Zundel 2011; Hill, & Levenhagen, 1995).

Metaphors are also an effective mechanism to generate new knowledge within disciplinary groups. As a recent study suggests, they are used abundantly in research projects in laboratory meetings to discuss issues and results of research, they provide hints and methodology to solve scientific problems, thus enhancing disciplinary knowledge. Most used by researchers in knowledge generation are those metaphors that bring in knowledge from very close domains, while those, which rely on distant domains, have an explanatory function (Dunbar 1997; 1999). Yet the role of metaphors in cross-disciplinary contexts is relatively neglected by literature on innovation.

In multidisciplinary processes of new knowledge combination, novelty recognition is just one problem to be solved. A more complex endeavour of knowledge building through combination has to be favoured. While the role of metaphors in novelty representation within a single discipline has been analyzed, less is understood when novelty is at the intersection of different disciplines. Thus, we want to contribute to the extant literature analyzing how metaphors emerge in research efforts at the intersection of disciplines.

Moreover being used as cognitive tool, metaphors might be challenged or even disconfirmed while the research of novelty proceeds. Indeed this dynamics is still under investigated. Thus we want to study the metaphors dynamics, focusing on the interplay between metaphors, interpretations and actions along a process of knowledge combination.

According to this aim, our approach is to adopt a cognitive view of metaphors that defines their structure in terms of mappings between a "source" concept and a "target" one (Lakoff, 1993). For example, the metaphor "Love is a journey" maps the source domain of journey to the target one of love. Elements in the source are mapped onto corresponding ones in the target (e.g. travelers -> lovers; the vehicle-> the love relation). The mapping goes beyond correspondences between elements. It transfers the knowledge we have about the source domain onto the target domain: a process that helps to reason about the target domain and generate new meaning (Grady, Oakley, & Coulson 1999) .

The transfer of knowledge made possible by the source-target mapping relies crucially on the perception of a similarity relationship between source and target (cf. Gregoire, & Shepherd, 2012). Handy is the distinction between types of similarity mapping, that separates *surface* similarity from *structural* similarity. Surface similarity refers to the resemblance across domains of basic attributes such as the color, shape or qualities (Markman, & Gentner 1997), whereas structural similarity (Gentner, 1983) refers to similarity only in the relational structure of the domains, hence in a predicative relationship that links at least two attributes in each domain. The perception and identification of the latter type are cognitively demanding when surface similarities are missing, scarce, or not transparent and cues to interpret different contexts are insufficient (Catrambone & Holyoak, 1989; Gentner 1989; Keane, Ledgeway, & Duff 1994). The distinction is important, because surface similarities can be misleading in the way we transfer knowledge across domains (Gilovich, 1981).

Recently also management scholars have looked at similarity recognition along with the dissimilarity between domains on the debate on the boundary conditions of the creative power of metaphors. For Oswick and colleagues, similarity recognition is a constraint for creativity, suggesting that the differences between domains represent the fertile ground from where to bring new knowledge and insights, hence other tropes that rely less on similar attributes or relations, such as the irony, would be more productive (Oswick, Keenoy, & Grant, 2002; Oswick, Fleming, & Hanlon, 2011). Instead, Cornelissen and his colleagues stress that is the metaphoric conception that moves the recognition of shared qualities across domains (Cornelissen 2004; 2005; 2006; Cornelissen and Clarke 2010) and that creativity instead is due to the distance between domains.

A cognitive view of the metaphor as a source-target mapping considerably blurs the boundaries between metaphors and other figures of speech such as analogy or simile (Holyoak, & Thagard 1996), attributing them to “a same basic human ability” (Fauconnier, & Turner, 2006) to make similarity-based mappings - a point many psychologists would challenge. We will not delve here in this controversial subject, as for our goals Lakoff’s (1993) mapping definition will suffice as a first approximation.

Instead, our study draws on a useful enrichment of the basic mapping structure introduced by Fauconnier and Turner (1998) in their work on conceptual integration, in order to understand the role of metaphors in processes of new knowledge development across distant domains. Fauconnier and Turner stress that the source-target mapping is just a special case of richer structures of conceptual integration, that relies on the combination of multiple sources into an integrative target (or, in their terminology, blend). So, for example, houseboat results from the mapping of two sources (the house and the boat) onto the new object (Goguen, 1999). The conceptual integration extension shows that metaphors are creative to the extent to which combining two semantic domains leads to construct correspondences, which were not there prior to the metaphoric thinking (Cornelissen, 2005). Specifically, this generalization of the source-target mapping will turn to be very helpful in what follows, since, as we shall see in multi-disciplinary contexts, a metaphorical target domain has to be simultaneously an integrative cognitive structure of multiple source domains to effectively mobilize different disciplinary knowledge.

Insert Figure 1 about here

Furthermore, Fauconnier and Turner have introduced a third and abstract domain (the generic space) that is a sort of common ground for the source domains, providing the basic structure within which the similarity between sources and their mapping to the target can be defined. In the houseboat case, the generic space might be the person-object-medium space of Figure 1 (adapted from Goguen, 1999). The notion of a generic space is important, because it shows that similarity between domains, needed to support their mapping onto the metaphoric target, can only arise within the broader structure of the metaphor itself (a point already clearly made in Lakoff, & Johnson, 1979).

Although a rich theoretical texture exists on the metaphor as a mechanism to map elements of a cognitive domain into another to generate new structure, that point to the heuristic power of such trope, yet this debate lacks of empirical evidence in multidisciplinary contexts, where metaphors can be used to generate knowledge that is new to each disciplinary field. And yet, there is still substantial lack of research on the interplay between metaphors and actions.

Therefore our intent is to study the dynamics of metaphors in the process of knowledge generation when this involves distant disciplines and we address the question of how metaphors work throughout this knowledge combination process. We aim at extending research on how metaphors emerge, how they frame activities and change, while they bridge multiple actors and disciplines over a period of time. We claim that metaphors emerge as a heuristic instrument and they not solely shed light on novel features in a specific discipline (Black, 1979; Cornelissen, 2004), but they help to shape a new cognitive domain by bringing a selection of knowledge from multiple input spaces (Fauconnier and Turner 1998) and to frame activities across different actors.

METHODS

Research Setting

The NEUR multidisciplinary research. According to our exploratory aim, that is to understand how metaphors emerge and to analyze their role in novel knowledge creation processes across distant disciplines, we adopted a theory-building qualitative research approach based on the case study of a eight-year neuroscience research project (Eisenhardt, 1989; Strauss and Corbin, 1990).

We investigated a setting in which knowledge creation and a multidisciplinary context were key features. The research setting was the NEUR[2] research project, a eight-year scientific research that started in 2002 with a national grant and two partners and continued with a further project financed by a leading European Institution in 2006, which involved three more research institutions and a commercial partner, located in six countries (Italy, Belgium, Switzerland, France, Israel, Germany).

The NEUR primarily aimed at developing a new generation of implants to repair damaged central nervous systems (CNS) tissues. Specific research goals branched off from the main one. Minor goals were to advance research on biophysical interactions between nanomaterials (carbon nanotubes) and neurons, to exploit nanomaterials as environment to favor damaged CNS tissues regeneration and to fabricate new neural microelectrodes. It was a research project at the scientific frontier of distant disciplines such as medicine, biology, engineering, chemistry and physics. The NEUR was also heterogeneous in the research practices of different laboratories and in differing types of experiment: in vivo, in vitro, and in silico, i.e., computer simulations carried out.

Whereas usually in multidisciplinary research, “various disciplines address scientific and social challenges independently” (OECD, 2010), NEUR succeeded in integrating and building novel knowledge by a deep effort of interaction across distant domains and different researchers and laboratories. In doing so, scientists achieved significant new understanding and novel results in the emergent research area of the modern nanotechnology application to biological systems.

----- Insert Table 1 around here -----

In our study we focused on the interaction of the three core disciplines, as shown in Table 1: medicine, specifically neurophysiology (henceforth NPH) with specialization on central nervous

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[2] All names have been encrypted to ensure confidentiality.

system, chemistry (CH) specialized on handling carbon nanostructures and engineering (ENG) with expertise on formal modeling of neural behavior. Informants included three key scientists, experts of each discipline. They were the key individuals to interview for three reasons: their advanced background in each of the three core disciplines, their pivotal role within the NEUR project – one of the three researchers was the scientific coordinator of the NEUR project – and their leading position in the laboratories in charge of main experiments and research advancements.

Key scientists. The chemist (CHt) at time of the NEUR's start led a laboratory operating in an Italian University. The laboratory was an organized, well-equipped space where, on average, more than 10 researchers worked. The CHt, full professor since 2002, had an excellent international standing. His contribution in advancing the field of nanoscience, internationally recognised, was based on large body of publications on first-tier chemical journals, as shown in Table 2. He was specialised in handling and functionalizing carbon nanomaterials by combining specific groups of atoms with the pristine carbonic structure to change its properties.

The neurophysiologist (NPHt) from 2002 to 2005 worked in a laboratory of research center part of an advanced school, that offers postgraduate training in scientific disciplines such as Physics, Mathematics and Neurosciences. Such laboratory was located in the same city of the university of the CHt. The NPHt is an Italian physician specialized in electrophysiology, assistant professor in the same university of the CHt since 2002. While she (NPHt) was appointed at the research center, the NPHt performed a research project on neuronal damaged tissues. In 2005 she successfully applied, as scientific coordinator for a European grant. Funds allowed the start-up of a new laboratory, where she conducted new experiments with two young researchers (doctoral students). Before the beginning of the NEUR project, the NPHt had several international publications in her specific research field. She was specialized in explants of neuronal and nervous tissues from rats and subsequent electrical recordings.

----------------- Insert Table 2 about here ---------------

The engineer (ENGr) was a postdoctoral researcher in a laboratory located in Switzerland until 2008. In this lab, experiments on electrophysiology were performed. In 2008, he moved to a Belgian University, where he was tenured as assistant professor and had the supervision of two young researchers in a new laboratory. At time of the start of the NEUR project, he was a young researcher on Bioengineering, field in which he obtained his doctorate. He joined NEUR in 2005. He worked on building and tuning mathematical models of neuronal activity, therefore he is familiar with electrophysiology recordings of population of neurons as he needs to test his models on 'real' data. Before he joined the NEUR project, he had 15 publications.

The time period analyzed starts in 2002 and covers eight years, from the birth of the original research idea, through two granted joint-research projects: a national project from 2002 to 2005 and a European one from 2006 to 2009. We focus on the three main experiments of two granted joint-research projects, an early one in 2003, a second successful one in 2005 that lead to the first joint article, and a third one in 2008, after the research team was enlarged, as shown in Figure 2.

Data Collection

We gathered data on goals, processes and scientists' interpretations along the entire length of the NEUR project. Data collection involved multiple sources (Eisenhard, 1989; Yin, 1984). Unlike standard data upon which studies on metaphors draw, that almost exclusively rely on textual and visual materials (cf. Gibbs, 2008), we added data sources bringing from the tradition of management case studies. We favored a cognitive rather than sociological reconstruction of facts, as they occurred prior to our entrance in the field.

We gathered data from four sources: (1) interviews with the leading scientists and other team members; (2) visit of laboratories and a direct observation to a half-year meeting; (3) archival data, including scientific publications, images, powerpoint presentations, sketches and other files provided by our informants; (4) press coverage, comprising written and audio interviews in the

Italian as well as International press, scientific journals, reviews, blogs and magazines. Two researchers conducted semi-structured and retrospective interviews of about 1.5 hours with the three key scientists, head of laboratories, who initiated the project, see Table 2. A fourth interview was performed with a former graduate student, member of the chemistry laboratory who played a crucial role during the second experiment (see paragraph). For the intent of reconstructing through each interviewee's narrative the representation of the project's turning points, images and metaphors, that guided respondents in dealing with previously not experienced situations, questions were mainly centered on facts and problem-solving activities spanning from the entrance of the interviewee in the scientific venture to the European project conclusion. However, much room was left for interviewees to freely reconstruct the steps of the research path, how they set up the experiments and interacted each other, how they interpreted results, the process of generation of ideas to advance the project and the role of each disciplinary background in a multidisciplinary research. Thus, personal perceptions and understanding of the process, the main steps and research ideas and metaphors emerged. To motivate scientists to give a thorough and accurate account of facts, we ensured confidentiality (Huber, & Power, 1985). After each interview, the three authors confronted their notes on salient parts on the interview; findings, ideas and interpretations over the major results were then triangulated by (Yin, 1984). One researcher directly observed a half-year meeting in which all groups presented their latest results. Herein, notes were taken, the audio recording was then transcribed, and we followed the same process of triangulation. Along with each interviews, a visit at the laboratory and follow-up informal interviews was performed with key scientists and some of their assistants for approximately 40 to 60 min each.

Among the secondary sources, we collected three interviews to the neurophysiologist and the engineer conducted by journalists during popular radio broadcasts on science. Another interview was part of the online podcast published in the website of Nature. These podcasts were published in 2005 and 2008. The audio recording of all interviews was transcribed verbatim.

We then were given access to textual and visual materials such as images produced by lab microscopes and notes produced by the three key scientists for internal communication purposes. We then gathered documents produced along the NEUR project for external scientific communication purposes, such as conferences, seminars, summer schools, peer-reviewed scientific publications. We also analyzed the final scientific report delivered to the granting institution at the end off NEUR project, together with a master of science thesis and a doctoral one developed on the same topic of the project.

To strengthen the internal validity of the accounts and to deepen the understanding, we relied only on information overlaps which must come from at least two sources and also must not be disconfirmed in any other (Miller, Cardinal, & Glick, 1997) and we combined retrospective accounts with real-time secondary sources (Leonard-Barton, 1990).

-------------------- Insert Table 3 about here ------------------

Follow-up emails and documents were sent to confirm interpretations and data collected. Moreover one document comprising our main results and interpretation of facts was sent to the NEUR scientific coordinator, discussed with her to gather feedbacks and comments and finally included in the final scientific report that the European project consortium sent to the granting institution.

Furthermore, the engineer enabled us to access his personal archive of images, sketches and presentations used internally at half-year meeting presentations and externally at conferences and seminars. The archive comprised almost 400 images and seven presentations. Over 80 percent of images were generated by the engineer’s work. Five presentations were made by the engineer, one by the chemist and the remaining by the neurophysiologist.

Finally documents and scientific publications were analyzed: the text and the images of all ten international publications[3] of the group of scientists – in the year from the 2005 to the 2009 – along with the latest eight scientific articles published by each key scientist (totally 24 papers of about 8 pages each) before joining the common scientific venture. These were used to establish prior knowledge, methodology and practices. In total we analyzed 34 articles. Nevertheless, two out of the 10 publications were finally excluded from the reconstruction of the story, because they were reviews of discipline-specific literatures. In their three experimental papers, we studied also the supporting information. We also analyzed articles in newspaper and magazines as well as online press of various types, such as blogs, scientific bulletins, online reviews among the others, that contained entire or excerpts of interviews to the key scientists. In total they were 18 articles, and one of these interviews was published in a scientific journal. They covered the period from their first joint publication in 2005 to the last one in 2009, online in late 2008. We analyzed and codified the scientists' statements reported in scientific articles and blogs where they were interviewed, in order to detect how they represented and disseminated their research results and the role likely played by metaphors. In addition, the 114-page final report, dated January 2010, encompassing all results with respect to the deliverables presented to the granting institution. This last document included the work of all six research partners, whereas we focus on the main three, because the role of the others was peripheral according to our research aims, as one partner was the provider of one tool for electrical recording that was not yet adopted in the phases we treat, another performed independent tests on living mice, and the remainder gave external support to the group of chemists based in Italy.

Data Analysis

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[3] Nine peer reviewed joint-articles and one single-authored literature review.

In our inductive approach, we reconstructed the main facts of three key experiments of the eight year NEUR research under investigation: the early experiment in 2003, the first successful one in 2005 that lead to the first joint publication, both funded by the national grant and the last experiment in 2008 carried out as part of the European research project (2006-2009). To identify overlaps and differences across disciplines prior to the research inception, we classify and count activities, methods and main concepts of the three disciplinary domains by the analysis of the eight articles written by the key scientists before their participation to the NEUR research.

We compared each other to build a conceptual framework (Eisenhardt, 1989). After completing the transcription of each interview, the three authors gathered to discuss their independently constructed viewpoint. A storyline was reconstructed and an interpretation of each experiment was then written in a narrative form with selected quotes of informants. A table summarizing facts with quotes from all sources as well as images to support facts, ideas and interpretations was created to make sense of the story and allow comparisons across given situations in time. Mainly focused on tracing back the causality of events and on deepening the understanding of phenomena, we incorporated both real-time data, such as images, presentations and articles, with retrospective accounts. This enhanced plausibility and coherence of interpretations and allowed us to control for time. Thus, we divided data by year or half-year, when significant events occurred.

Finally follow up documents and emails were sent to scientists to discuss and confirm the interpretation and to increase internal validity.

We chose to study this single case with in depth analysis, because it is a unique case of a successful interdisciplinary radical research over several years, it has a deep potential for theoretical contributions (Siggelkow 2007) on the role of metaphors in knowledge combination processes and their dynamics.

After an iterative process of analysis, data on experiments and NEUR researchers interpretations were cross-checked several times. In order to give a clear account that separates facts from interpretations, we adopted a within-case analysis (Miles, & Huberman, 1984), and more specifically a two-order concepts of narration (Van Maanen, 1979) .

In the following sections each key experiment is reconstructed to understand the role played by metaphors. In each main phase we analyze in depth the emergence of a metaphor, how it guides research ideas, the experimental setting, and defines the constraints to which each specific disciplinary group adapts. Moreover we study how new metaphors are developed and respond to new problems or advancements and to the changing composition of the network of actors involved.

FINDINGS

At the NEUR research inception: images and surface similarities

In 2002 the two leading researchers that generated the research idea (CHt and NPHt) were working separately in different institutions and locations and they did not know each other. However an incidental exchange of images was the trigger for their decision to develop a joint experiment.

At that time the CHt was asked to attach a protein on carbon nanotubes to favor the interaction with neurons in order to start experimenting the combination of the two materials. As shown in Table 1, the CH lab's expertise was in manipulating nanotubes, whereas they never handled neuronal tissues, therefore CHt contacted NPHt's supervisor who worked in an important research institute. The researcher suggested NPHt's (his post-doctoral student) to start a conversation with CHt. NPHt was, in fact, a young scientist whose activity was dedicated to understand the electrical behavior of nervous tissues. She dealt with tissues explanted from mice and was familiar with electrical recording tools, pharmaceutical drugs to control neuronal electrical activity and microscopic analysis of living cells.

The images exchanged by the two scientists were two microscopy pictures of carbon nanotubes and neurons, respectively taken by the CH and the NPH laboratories. The casual comparison of the two pictures showed an unexpected similarity between the two objects.

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> "Watching the images, we looked at each other (the NPHt and the CHt) and said these two (nanotubes and neurons) look incredibly alike"(NPHt).

By observing images they noticed the surface similarity between the chemical compound and organic material, as seen on the electronic microscope, see Figure 3, and therefore they decided that it made sense try to combine the two materials and start a first joint experiment.

> "The idea of putting together carbon nanotubes and neurones came first of all because of their structural (surface in the literature) similarities … [n]eurite elongations are reminiscent of the cylindrical shape of carbon nanotubes" (CHt – Pr2Ch05[4]).

The early experiment of 2003 and the *electrical wire* metaphor (metaphor 1)

They initially decided to perform a joint experiment, but it took one year and a half to design it. The two fields were distant and it was the first time that each scientist had to consider the other discipline in one of his/her own experiments. The non-obvious superficial resemblance between the two representations at the nanoscale was quickly foregone by the CHt and the NPHt who were, instead, attracted by the morphological or superficial–similarities of the two compounds, more specifically the roughness and the branching, see Figure 2, and by a structural similarity (Gentner 1983), that is the idea that nanotubes, as well as neuronal branching, could transport electric signals. However, apart from what they perceived as similar, they knew little about the other scientist's

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[4] Secondary source interviews' code.

materials properties and behavior, thus notwithstanding the inspiring role of the metaphor, they had to overcome several challenges to design the experiment.

Their effort in identifying possible bridges were focused on reducing the toxicity of the carbon structure and, on the other disciplinary hand, on the way to bridge a broken neuronal tissue with carbon nanotubes. During this period, the NPHt and the CHt worked separately, but sharing reviews, articles and books in order to understand specific features of each other's material domains useful to set up the experiment. To summarize, in the CH lab, it is known how nanotubes might be manipulated in order to be pure and biocompatible, but there was no knowledge about neuronal behavior, properties and requirements in order to make neurons survive in vitro, and vice versa for the NPH lab. The image of electric wire led the NPHt to understand that a structural relation could be traced between carbon nanotubes and neurons: both materials conduct electricity.

> 'At least at the beginning, I think that it was easier for them (neurophysiologists) to understand, because of the assumption that nanotubes are like tiny electric wires connecting two neurons that communicate through electric signals.' (CHt)

The *electric wire* metaphor was triggered by the superficial similarities recognition and developed around the reconstruction of a deeper, structural one, which made salient a common feature of the biological and artificial material, the electrical conductivity, and suggested a common functional property of both: conducting the electrochemical signal of neurons. Hence the *electric wire* metaphor prompted the scientists to infer that nanotubes might act as substitutes of the dendritic connection.

The idea of exploiting the common relation – the connectivity property – of the two materials was pivotal in the first two years of the research, namely in the setup of the first experiment. The first experiment was created on the basis of neurophysiologic prior experimental results according to which neuronal tissues placed apart tended to grow more towards each other than in other directions. Therefore they tested the hypothesis that nanotubes like 'tiny electrical wires' might connect two slices of neuronal tissue set far enough not to be able to reconnect otherwise. The preparation work was divided between the two laboratories. The CHt functionalized nanotubes by making three adjustments to transform them into a biocompatible compound, adhesive to glass and non-water-soluble: adaptations that yielded two within-discipline publications for the CH group. Then, the CHt provided this compound to the NPHt who was in charge to conduct in vitro experiments in her laboratory.

Such experiments failed. Following an established neurophysiologic experimental approach, a layer of protein material was put between neurons and carbon nanotubes, however it impeded the electrical signal to flow from neurons to nanotubes. Therefore, for a successful result, it should have been dropped. The *electric wire* metaphor, while successfully inspired the first joint experimental attempt, and the CH's work on nanotubes to finalize them for the experiment, they it did not help to fully reframe the standard experimental procedures used in NPH experiments.

The 2005 experiment and the *scaffold* metaphor (metaphor 2)

In 2003 after the first experiment, the two researchers applied for a regional grant, committing themselves to a joint research project to study nanostructures of carbon and neural circuit formation. When the grant was awarded, they designed the new experiment drawing on previous results, specifically trying to understand what were the obstacles. This aim led the scientists to intensify their effort on the project and the frequency of their interaction with different solutions: joint-seminars and lectures, and the appointment of a CH graduate student to the project. Exchanging reading materials and increasing their interactions facilitated the identification of the material that insulated neurons from nanotubes.

Due to his longstanding research expertise, CHts was aware of the potential of the carbon structure as platform onto which developing a new generation of innovative medical therapies. Nanotubes had a set of properties that allowed a new association within the CHt's mind.

Nanotubes' have a porous and fractal-like configuration, constant along their length and apt to be chemically functionalized with molecules in order to change their properties. This feature combined with a proven compatibility with physiological conditions makes them potential devices to create nano-scale prosthesis, and adapt to be the 'scaffold' for neuronal growth and axonal regeneration. This *scaffold* metaphor was mentioned in an article of the CH group published in 1998 in which they refer to fullerene, the genitor of nanotubes, as potential scaffold for tissue growth, see Table 1. Thus due to the *scaffold* metaphor, some ideas from the broad knowledge domain of "tissue engineering", a hot topic in chemistry, especially with respect to carbon nanotubes (Harrison, & Atala, 2007), were brought in at the beginning of the second experiment.

--------- Insert Figure 4 about here-------

> '[H]e (CHt) 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 functionalised. He had this idea.' (NPHt)

The new experiment was developed on the basis of the *scaffold* metaphor by the chemistry laboratory, which brought in a different experimental approach, the removal of intermediate layers between neurons and nanotubes, and boosted the activity by involving a new young researcher.

The new experimental setting designed one year later consisted in neurons deposited directly onto a layer of carbon nanotubes in contrast with the prior experimental operative procedures that was one the main causes of the contradictory results: the two materials did not "speak to each other" (as they were interpreted by the NPHt). Electrical activity was then recorded. On a control glass, neurons were deposited directly on the borosilicate glass. Results showed a boosted neuronal activity in presence of nanotubes. These findings surprised both scientists and yielded the first joint publication in 2005.

> "In the long term, our results will prompt the development of new tissue engineering strategies." (NPHt – Pr2Nph05).

The interpretation of results was framed under the lens of the *scaffold* metaphor of neuronal growth and regeneration to re-establish the connection after spinal injuries. Furthermore the new experimental setup required the advancement of the technique of explants of neurons (NPH) and the control of layer of nanotubes' thickness (CH). Both advancements were crystallized in the joint published work, as the experiment had successful, although puzzling, results.

The 2008 experiment and the *percolation* metaphor (metaphor 3)

The increased neuronal activity when neurons were coupled with nanotubes was puzzling because it was incompatible with the simple picture of dyadic relationships among neurons, implied by both metaphors of the *electric wire* and of the *scaffold.* Therefore the two scientists needed to look for new competences outside their own disciplinary domains. They decided to broaden the theoretical background of the team by drawing on a different discipline: electrical engineering. Thereby, in the 2005, the NPHt contacted the ENGr who got involved in the project with the role of developing mathematical models to predict the neuronal electrical activity.

> "At that time she (NPHt) had the curiosity to know what in the nanotubes enhanced the neuronal [electrical] activity and, naturally, we (chemists) wanted to understand what [was the] quality of the nanotubes we were using [that provoked that effect] in order to favour that [electrical] activity." (CHt)

The group thus worked on the understanding of the rationale of such puzzling phenomenon. To understand the cause of the boosted electrical activity, chemists' and neurophysiologists' skills, tools and knowledge bases were not sufficient. Since the phenomenon pointed to the electrical properties of nanomaterials, recruiting knowledge resources capable to model the interaction at the interface was crucial. The neurophysiologist recognized that integrating a new competence in the group is necessary to understand what happens at the nanoscale. Also, the CHt felt the need to move from a "phenomenological" (in the words of CHt) leading metaphor to a better specified frame that could act as a full model of the process, generating quantitative predictions and not only qualitative inferences. Recruiting the ENGr trained in the simulation of neuronal circuits provided the key source of knowledge to accomplish such step ahead.

A new research project was funded by the European grant (2006-2009) and the team was formed with the aim to develop implants, which may repair damages at the central nervous system. It encompassed new knowledge bases among which engineering was central in the design of experiments.

A new language orchestrated the activities of members directed by mathematical formulas and theoretically-driven by the ideas of ENGr and his small group, emphasizing the role of electrical circuits and networks of connections. The trigger for a new round of experiments came from such background.

> 'I found an article by Kirkpatrick, a very famous physicist, who wrote an article in the 70s on percolation and electric conduction... what percolation really means? He basically talked of a resistive lattice and equivalent circuits, resistors, he used the elements I was comfortable with. And he showed how there is an electric path between two distinct points'. (ENGr)

Microscopy images, see Figure 3, provided the material context where such an intuition of a discontinuous interaction between materials is visible, therefore they support a deeper structural similarity between the percolation theory idea and the combination of artificial and neuronal graft. The new visionary idea brought by the metaphor of *percolation* was the passage of ions between any two points of the organic and the artificial layer.

> '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.' (ENGr)

The ENGr imagined the interaction between the neuron and a batch of carbon nanotubes like an 'electric wire sitting on other electric wires'. Moreover this electrical metaphor was enhanced by the new conception of nanotubes that described them as ‘a dispersion of tiny wires, infinitesimal needles, electrically conductive’ (ENGr – Au11Eng08) and such image was allowed by the view of new images.

Through the metaphor of *percolation*, the two compounds were treated as homogeneous layers that might leak electricity at any point, therefore the electric current did not necessarily stream in one determinate direction. To test the hypothesis of the shortcut of current that returns to where it started, after leaking through the carbon nanotube substrate, a sequence of intermediate steps was required. The development of a way to describe phenomena under the language of electrical equivalent led to a mathematical formulation of possible interactions and, therefore, to a model describing the coupling between the neuron and nanotubes. Such an intertwined interaction between theoretical modeling and experimental data triggered by the *percolation* metaphor, required a tighter interaction between the two ENG and NPH laboratories. This implied a joint planning of the experimental design and controls and was one of the main problems to overcome in this phase of the project.

> ‘[T]he fact that it worked surprised me, because I thought: this (hypothesis) is science-fiction, this is a cartoon. It is not possible, there must be other explanations. And recently, few weeks ago, the NPHt carried out another experiment and it seems that another hypothesis that made me sleepless will be rejected.’ (ENGr)

A new type of electrical measurement was adopted to capture the electric tension at two diverse points of the neuronal surface.

The metaphor of *percolation* produced important results that confirmed the hypothesis of a leaking current from the neuronal membrane via nanotubes back into the soma, where it originated. Such work yielded the group’s most relevant publication and a first theoretical model of interaction between the neuron and nanotubes.

DISCUSSION

In this section, we discuss the research findings addressing the research questions on how metaphors emerge in a context with multiple knowledge domains, how they affect action and what is, in turn, the effect of actions on metaphors. With respect to the extant literature, our accounts provide new humus to contribute on the theories of metaphors' role in knowledge combination processes.

The emergence dynamics of metaphors in interdisciplinary context

Our research findings show how metaphors emerge. From a point of view of metaphor generation dynamics, it seems to occur in two stages. In the first stage, bridging of distant disciplinary domains is based on the recognition of surface similarities, triggered by images. In a subsequent stage, the emergence of a common structure, i.e., the generic space, helps to detect even structural similarities.

The Electric wire Metaphor. Through the selective analysis of different microscopy images produced at the same scale of magnitude in each lab, the two scientists were surprised by the resemblance of the two images, and guided by their prior scientific background (Styles, 1997) they recognized surface similarities between the two objects: analogous branching structure, roughness of the surface, and elongations with similar caliber. Such morphological properties of nanotubes and neurons trigger a between-domains mapping and the reconstruction of a generic space that draws on electricity domain. This leads to a more in-depth analysis and to the recognition of a higher level (structural) similarity around which the first experiment is generated: the electrical conductivity.

Similarity detection and cross-domain mapping is the first step of a metaphoric thought (Wolff and Gentner 2011). To make sense as a metaphor, projections of parts of the input domains of chemistry and neurophysiology are blended together through the common ground of the generic space of electricity.

At the same time the selective nature of the *electric wire* metaphor hides some relevant problems relative to the integration of organic (neurons) and inorganic (nanotubes) objects. Thus while on one hand it inspired the project stet up showing the two objects' similarities, on the other it was not sufficient to design a successful experimental approach.

The Scaffold Metaphor. After the disciplinary work of adaptation made during the first phase of the collaboration, nanotubes present new properties matching those of a scaffold for tissue regeneration. As shown in Table 1, prior knowledge of scaffolds, associated to carbon molecule genitor to nanotubes, is already part of the CH group's background. Similar morphological attributes between the scaffolds and carbon nanotubes are matrix-wise, biocompatible meshes with a porous surface. In the domain of tissue engineering, scaffolds are used to support tissue formation or regeneration, and this idea is compatible yet different with the aims of the second experiment, which is to provide a functional reconnections of injured neurons. The common relational structure, generic space, is the artificial surface that provides functional support to nervous tissues.

The Percolation Metaphor. Microscopy images at different magnification show discontinuous and frequent junctures between the surface of a neuronal dendrite and that of a nanotube, which is rough enough to pierce the organic material in different points. The need of a deeper understanding of the puzzling boosted neuronal activity that derived from the research advancements drives the search of new resources and ideas. The new *percolation* metaphor exploits surface similarities that consider nanotubes and neurons as a homogeneous domain and associate them to the knowledge domain of electricity. On the one hand there is a network of junctures between neurons and nanotubes (what the ENGr mentions as 'electrical wires sitting over other electrical wires'), on the other hand the theoretical framework of percolation theory that speaks about the connections in resistive lattice. Such a cross-domain mapping allow to draw on the general idea of the percolation theory, which becomes the generic space: an electrical circuit connects any two points, if there are enough connections – junctures – in the lattice.

Like in the first metaphor, the generic space is based on the electrical domain, from which through an enriched cognition and a series of highly magnified images the group is able to extract a new generative metaphor: the *percolation* one, that in some ways comprises the past one of the 'tiny electrical wire'.

Findings show how the emergence of metaphors stems from the recognition of surface similarity that favors the identification of a common relational structure across domains. The role of images is central in this process. They help to map distant concepts and trigger structural similarities. Findings also show that metaphors are organized around the generic space.

Centrality of images and generic space

Our findings shed light on two key aspect of metaphors emergence in a interdisciplinary contest. First, research results show how images provide the ground for similarity recognition, overcoming the difficulties of bridging distant disciplinary domains that do not share a common language. Secondly, findings suggest that in the emergence of metaphors, the identification of an abstract generic space is a key step allowing the definition of a common ground for concepts and for actors' communication and action.

Different disciplinary groups or communities of practices, well represented by each scientific group, see Table 1, can overcome boundaries by means of shared representations, such as images, that accomplish their function as they translate ideas, mediate interaction and provide a context (Ewenstein & Whyte, 2009; Henderson 1991). Yet, images serve another important function: they facilitate metaphoric thinking. This phenomenon occurs through a complex series of mental steps. First, images make apparent the nonobvious (cf. Shane, 2000) links between domains, by providing the context to match a familiar knowledge background with visual aspects of an unfamiliar one. This occurs because images are effective means to retrieve knowledge stacked in individuals' memory (Keane et al. 1994), providing the ground for the vision of morphological characteristics of unfamiliar domains, that are interpreted by means of that knowledge. Recognized superficial similarities drive the establishment of further mental associations between objects: a symmetric mental process of similarity detection at the initial stage of the metaphor generation (Wolff and Gentner 2011). Secondly, in a later stage, when surface similarities are established, common structures between inputs emerge. The identification of the common structure is central in the process of metaphor generation, and it becomes a cognitive resource that might be available as a reference source domain eventually for solving future puzzle and give structure to future metaphors and solutions. As cognitive literature stresses, structural similarities tend to be cognitively demanding in absence of multiple cues or a guidance (Catrambone, & Holyoak 1989; Gentner 1989), therefore, in absence of evident surface similarities, the emergence of a generic space is hindered.

In summary, images are the tools that provides interpretable signs for scientists to make sense of unfamiliar domains, and specifically images facilitate a correspondence-based emergence of metaphors (Cornelissen, 2005) by allowing the recognition of similar attributes across domains. This similar attributes in turn facilitate the emergence of a common generic space on which new conceptual combination can be grounded. This sustains the revelation of subsequent and more profound – and at times successful – transfers of inferences and relations between domains. Therefore images trigger a creative process that starts with the identification of bridges across distant domains, goes through the generation of a generic space and a relational structure and sometimes it is completed by the adoption of inferences from the source domain into the target. The role of the endowment of theories of the group members is to mediate the similarity recognition and the capacity of drawing inferences.

The impact of metaphors on actions

In this paragraph to understand the dynamics of metaphors throughout the research projects, we address the heuristic value of metaphors focusing on how they impact on actions. The strength of metaphors to provoke and drive collective actions has been stressed for (Hill & Levenhagen 1995; Cornelissen, & Clarke 2010; Cornelissen et al. 2011) the capacity of giving familiar and legitimate frames to new contexts, and therefore to drive new directions of action. We provide further evidence and extend prior literature by showing how metaphors impact on decisions and actors' network.

As an organizer of the integration of knowledge domains, the metaphor creates a new multi-disciplinary shared interest upon the creation of an experimental artifact, a common field in which practices and meanings do not necessarily merge but can still be coordinated. While experimental practices in neurophysiology and chemistry remain to some extent opaque to each other during the project, metaphors organize a common language allowing to conceive and evaluate experiments performed separately in each lab.

Due to the *electric wire* metaphor, the first experiment has to be set up. Adapting distant domains and making inputs compatible with each other is necessary to perform the experiments. At the earliest phase of the collaboration, nanotubes are toxic for neurons due to traces of heavy metals. Moreover, they must be steadily hooked to the experimental glass not to harm neurons. Ultimately, nanotubes are also water-soluble and they disappear when combined with the organic solution containing neurons. Disciplinary and experimental adjustments are necessary: nanotubes are depurated and made non-toxic, and adhesive to glass.

In the second phase, the *scaffold* metaphor suggested the opportunity to merge the two materials instead of having a layer in between, which guided the redesign of the new experiment and further disciplinary work by both the NPH and the CH laboratories. The CHt controls the thickness of the nanotubes' layer, the NPHt modifies the explantation technique to adapt it to the new experimental approach.

Moverover the metaphors' impact on the experimental design, its controls and methodology can be identified analyzing the third metaphor, which utilizes the theory of percolation to infer electrical shortcuts in the network. To test a hypothesis of percolation, the outcome of an innovative electrical measurement conducted on a neuron has to be tuned with the results of mathematical simulations. While Dunbar (1997,1999) shows the carry-over of methodology by means of the metaphoric thinking, we see that the metaphoric conception guides the generation of an *ad hoc* methodology. Metaphors have an impact not only on experimental adjustments, but also on the network of resources to mobilize and recruit, such as researchers. For instance after the first successful experiment, the CH and NPH cognitive bases are not able to explain enhanced neuronal activity, therefore the two scientists look within their immediate social network for actors who may help framing the puzzle under a different perspective.

The impact of actions on metaphors

Finding show how, in the development of the project, metaphors not only impact on actions, but in turn are affected by research puzzles and advancements; metaphors change their role and their functions, give heuristic contributions and are also rhetorically used to disseminate results to multiple types of audience. Actions have a two-fold impact on metaphors: on the one hand, actions modify the cognition of domains either transforming inputs or changing the composition of theories; on the other hand, actions are the means by which scientists exploit of the heuristic power of a metaphor, paving the way for a rhetorical use. Yet, the generic space arose through the metaphor is still a cognitive asset of the group that can be levered, along with its metaphor, in successive phases.

To show the effect of actions on the cognition and therefore on subsequent metaphors, we consider the final part of the blend, which is the elaboration (Fauconnier and Turner 1998), in which a mental (and material) simulation is run according to the metaphoric (experimental) rules that may generate results, puzzles and further thinking. Experimental actions modify material properties and scientists' cognition of the input domain, and since metaphors emerge on the basis of the latter, actions have a direct consequence on metaphoric production. For example, in the second stage, the transformation that carbon nanotubes have previously undergone making them biocompatible, non-water-soluble, and adhesive to glass enhances their similarity with scaffolds, thus triggering the emergence of the metaphor.

Also changes of knowledge bases modify the endowment of theories held by the members, thus enabling members to draw on a broader (and deeper) sets of domains and causal relations. One clear example is the third metaphor that stems from a deeper knowledge of electrical engineering. Scientists nest the first metaphor of the nanotube as an electric wire in a larger contexts of metaphors to produce a more complex mapping across multiple domains. In this phase, a neuron is also a tiny electric wire which sits on other electric wires – nanotubes – thus creating an electric network. And the electric network calls for a mapping with the domain of percolation, namely with the resistive lattice that belongs to the article by Kirkpatrick. Thus the recruitment of a new scientist that broadened and deepened the knowledge available gave rise to set of metaphors that construct a new generic space.

After producing structural relationships between domains that are used for disciplinary and cross-disciplinary scientific advancements, the use of metaphors in the communication of results with explanatory (Dunbar 1997, 1999) or legitimating intents (Gentner & Markman 1997) has already been analyzed by the literature. Along this stream, the analysis of radio and press interviews of scientists confirms that metaphors recur abundantly to express processes that are complex and unfamiliar to the audience in a easy and evocative way. However, they are also part of technical and peer-attended discourses. As part of their conversation, metaphors are *lively* (Ricoeur, 2003) not just in the rhetoric of the group, but as a cognitive tool to explore the frontier of knowledge and to combine different cognitive domains. Under this lens and because of the actions that scientists make, *worn-out* metaphors (Ricoeur, 2003), that should add no novel meanings, become useful and provide new meaning if the cognition of domains is enriched and new inferences may be made.

Thus, the heuristic power of a metaphor may be reinforced and enhanced if members' endowment of theories is enriched. If *lively* is the metaphor in which new meaning can be attributed, in which the conventional "cultural usage" do not decide "on the figurative sense of certain expressions" (2003: 225), we must point out that it is the cognitive richness of inputs domains that determines when a metaphor is still lively.

Tying the heuristic power of metaphor to the cognition of domains, namely showing the cyclic link between cognition, metaphor generation with actions that, in turn, modify the cognition may fade the dispute (Cornelissen 2005; 2006; Oswick et al. 2002; Oswick & Jones 2006) on the most apt trope for knowledge production, as also the same metaphor can be regenerated and inform new theoretical extraction. Consistent with both the comparison model of metaphor (Oswick et al. 2002) and the interaction model (Black 1962; Cornelissen 2006), our finding show that recognized similarities are a first step of metaphoric thinking. They inform and (constrain) the extraction of a deeper relational structure between domains. This is generates the metaphor that enables the import of inferences to test in novel environments, such as the percolation hypothesis tested in the novel setting of neurons and nanotubes. We show that the heuristic value resides in two phases. The first occurs with the work of adaptation made on the input space to allow the combination of inputs. And this allows disciplinary knowledge development. The second consists in the combination of input domains, in which occurs the production of cross-disciplinary knowledge.

Being dynamic the cognition of the input domains, different cognitive endowments may inform different or nested metaphors, thus extending their creative power. For this reason, we believe that more critical point is the ability to see structural similarities, as they are the motor of the action.

CONCLUSIONS AND LIMITATIONS

Our paper shows that metaphors can effectively be mechanisms for knowledge production and exploration at the frontier of different disciplines, and describe the process of emergence of metaphors, their heuristic value for both disciplinary and cross-disciplinary communities, their guidance for scientific actions in multiple disciplinary setting does not come without flaws.

Some critics may say that we omitted to analyze in depth the structure of the metaphor. We decided to undertake a different course due to our research aim on metaphors' dynamics. However our evidence might provide some interesting insight for further research delving on the theoretical debate that separate the vision of those who believe that metaphors are not the most creative tropes for knowledge production, being constrained by similarities (Oswick et al. 2002; 2006), and others who claim that through metaphors it is possible to go beyond the sum of the domains (Cornelissen 2004; 2005; 2006).This argument is definitely worthy to dedicate new energies and efforts and we believe that our data may give interesting information.

Our work enriches the soil of the scholars who indentified metaphors and analogies as players for innovation breakthroughs and scientific discoveries (Dunbar, 1997; 1999; Gassmann, & Zeschky 2008; Knoor, 1980), although our focus has been on how metaphors contribute to the combination of diverse sources of knowledge bases and their transformation (Carlile, 2002) guiding the action of actors belonging to different scientific communities.

We extend the understanding of images as fertile objects for creating a common ground between different social worlds (Ewenstein & Whyte 2009; Henderson, 1991). Images are the ground in which similarities are recognized, thus, setting the stage for the generation of metaphors.

Our research has some limits and two natural lines of evolution. Our qualitative investigation could be enriched and complemented by a quantitative analysis of the textual material produced along the project. Formal text analysis could help to find regularities in language used by researchers and to understand, with a more fine-grained lens, how metaphors evolved.

A second line of research should investigate how metaphors are embedded in a context of social relationships and artifacts. Leading metaphors, scientific tools and the social network of scientists mobilized clearly coevolve along the project. Their interaction deserves closer analysis through an ethnographic approach.

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Figure 1. A textual blend, an adaptation from Goguen, 1999.

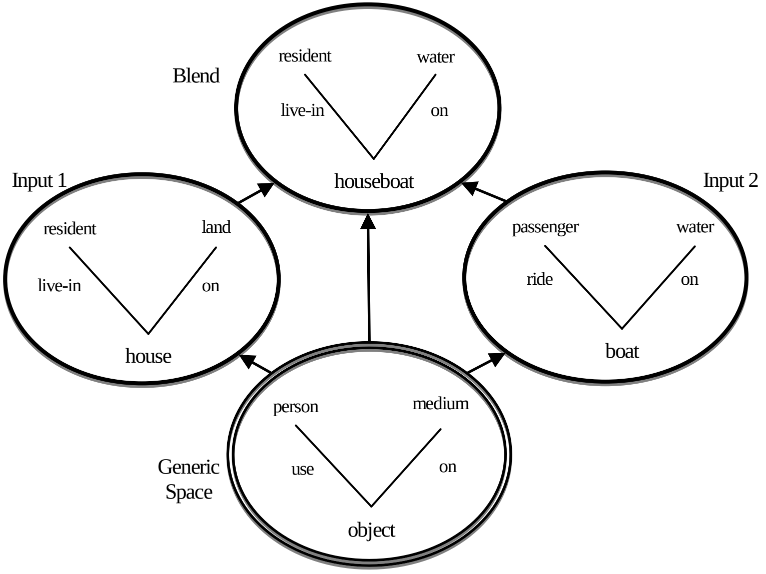

Figure 2. Storyline of the research project.

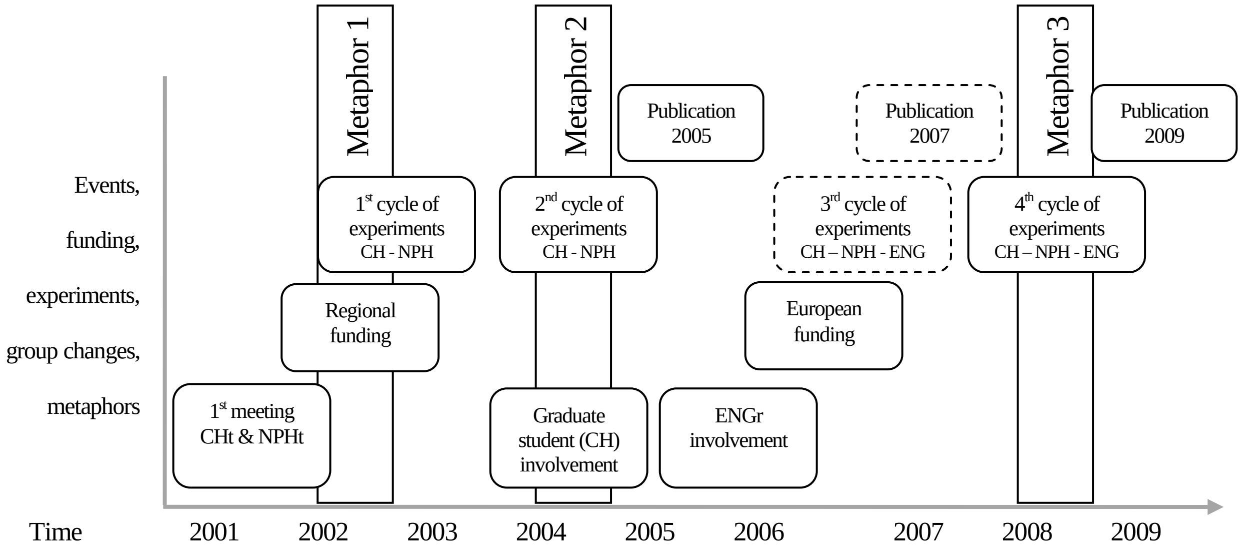

Figure 3. A batch of carbon nanotubes (left) and hippocampal neurons under immunofluorescence (right) at the Scanning Electron Microscopy (SEM), with the courtesy of NPH group.

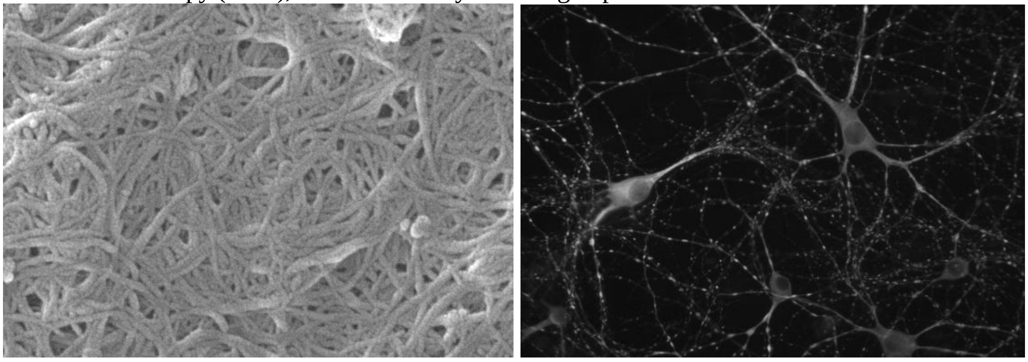

Figure 4. Metaphors: the generic space and additional requirements

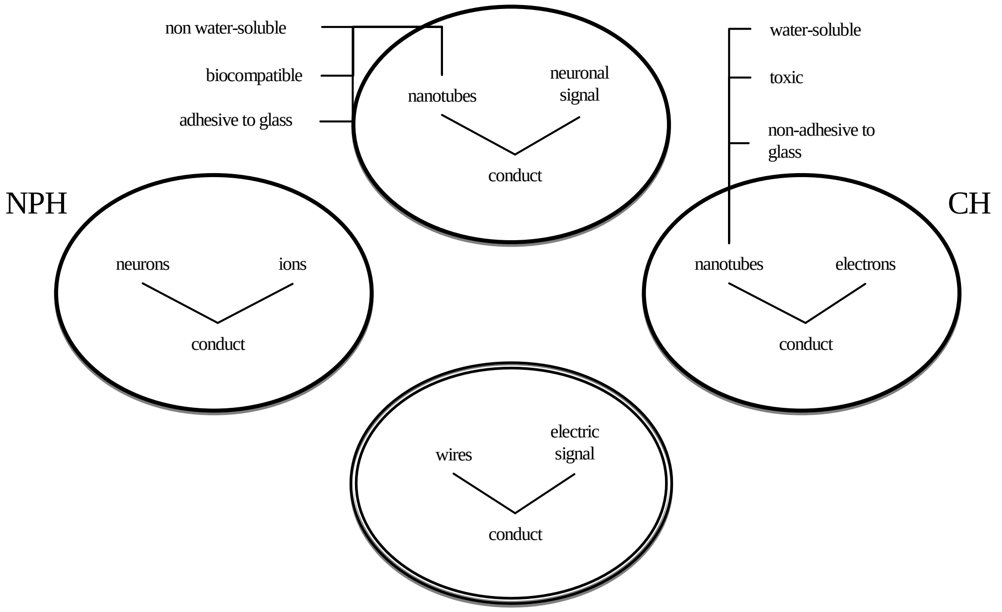

Table 2. Research Setting

Laboratory - main field	Chemistry (CH) lab	Neurophysiology (NPh) lab	Engineering (ENG) lab
main research area	functionalisation of nanotubes	in-vitro experiment with neurons	computational simulations of neuronal models
Referent	head of the lab	assistant till 2005, head of the lab since then	assistant in Switzerland (2005-2009), head of the lab in Belgium (2008-2009)
Location	Italian University (2002-2009)	Italian Research Centre (2002-2005), Italian University (2005-2009)	Swiss University and Belgian University
Size	10-15 permanent researchers	0-2 researchers till 2005, 2 permanent researchers since 2005	1 researcher in Switzerland, 2 in Belgium
Tenure of referent when he or she joined the project	full professor	assistant professor	assistant professor
Publications of the referent before joining the group*	157	15	15

*Google Scholar ® and curricula vitae have been used as a source of information, data have been screened afterwards

Table 3. Data sources

Type of Data	**Total**	**Detailed**
Interviews length verbatim transcribed [informal] {radio} (duration)	4 + [4] + {2} (5h 35')	(CHt & CH - assistant); (NPHt); (ENGr); [1 CHt]; [1 NPHt]; [1 NPH assistant]; [1 ENGr] ; 3 visits at laboratories
Group meeting participation verbatim transcribed (length)	1 (3h 29m)	
Scientific publications	34	10 (joint work) – 24 (8 for each group) to map prior knowledge
Powerpoint presentations (pages)	7 (171 pages)	1 (24) CH, 1 (15) NPH, 5 (132) ENG
Article of press coverage	18	7 in English, 11 in Italian
Images	391	29 CH, 37 NPH, 325 ENG
Thesis (pages)	2 (252)	162(Ph.D.), 90 (M.Sc.)
European Report (pages)	1 (114)	

Table 1. Disciplinary knowledge.

techniques/tools/activities	**NPH**	**CH**	**ENG**
voltage	8	1	8
in vitro (or on glass)	8	1	2
statistics (st. significance/ test / st. analysis)	8	0	6
recording (single cell / population)	8	0	2
resistance	8	0	2
statistical analysis section	8	0	1
explants	6	0	0
pharmacology (blocks, inhibitors, facilitators)	5	0	1
inverted microscope	4	0	0
noise	2	0	7
similarity of spikes / bursts	2	0	2
electron microscope (TEM)	1	3	0
in silico simulation & algorithms	1	0	5
correlation	1	0	3
epifluorescence microscopy	1	0	0
infrared microscope	1	0	0
laser scanning microscope	1	0	0
videomicroscope	1	0	0
carbon structures (fullerene/nanotubes)	0	8	0
functionalization	0	8	0
atomic force microscope	0	2	0
magnetic force microscope	0	1	0
scaffold	0	1	0
scanning probe microscope	0	1	0
presence of equations	0	0	8
microscope (not specified)	0	0	1

Techniques/tools/activities have been counted (1) if present, one or more times, in a scientific publication. E.g., correlation has been mentioned one or multiple times in an article of NPH and in three article by the ENG group.