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Metaphors are more popular than ever in the study of scientific reasoning and culture because of their innovative and generative powers. It is assumed, that novel scientific metaphors become more clear and well-defined, as they become more established and conventional within the relevant discourses. But we still need empirical studies of the career of metaphors in scientific discourse and of the communicative strategies identifying a given metaphor as either novel or conventional. This paper presents a case study of the discursive development of the metaphor of "the genetic code" from the introduction of the metaphor to its establishment as an entire network of interrelated conventional metaphors. Not only do the strategies in communicating the metaphor change as the metaphor becomes more established within the discourse, but the genres in which the metaphor is developed and interpreted change too during the career of the metaphor. Whereas the standard scientific article is central in experimentally researching and explaining the metaphor, a mixture of more popular scientific genres dominates in the innovative conceptual development of the metaphor.

1. Introduction

Developing metaphors

Research in scientific reasoning and knowledge production has celebrated scientific metaphor and analogy for their innovative, problem-solving and generative powers (see among others: Black, 1962; Hesse, 1966; Leatherdale, 1974; Knorr Cetina, 1981; Maasen, Mendelsohn and Weingart, 1995; Keller, 1995, 2000). Analogical or metaphorical reasoning describes a process in which a given phenomenon is compared to another otherwise totally unrelated phenomenon, and pictured as sharing central attributes or relations. In doing so, in seeing for instance a specific phenomenon under research (for instance a particular type of moving gene) in a different light (as hitchhikers) might bring different and even unexpected aspects of the research object to the center of attention (certain genes may travel in the genome by using other genes). Schön (1963, 1995) calls this process a process of "seeing as." Whether the process is regarded as analogical or metaphorical depends on exactly how unrelated the two compared phenomena are considered to be. The more literal the difference

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between the categories to which the compared phenomena belong, the more metaphorical the comparison is considered to be.

The process is often set off by the researcher struggling to understand a given phenomenon or set of data, and then suddenly seeing and being able to explain these data by using a metaphor. Tauber and Chernyak (1991: 9) describe, for instance, how the immunologist Elie Metchnikoff during observation of certain mobile cells suddenly was struck by the idea that similar cells might "serve in the defense of the organism against intruders." Metchnikoff spent the next 25 years developing this theory of cells at war. The construction of such a metaphor is innovative and generative in two ways: it generates new insight, but it is also capable of generating additional metaphors (which then again can be generative of even more insight and metaphors). In the end, the result might be a central root-metaphor (Pepper, 1942) surrounded by a network of related metaphors.

Focusing mainly on these innovative generative aspects, the majority of the literature on metaphors in science tends to disregard the study of the additional development of the metaphors. Consequently, the subsequent hard and dirty work of testing, elaborating, confirming, discharging, adjusting, combining, formulating, arguing, communicating and establishing specific scientific metaphors is rarely considered, neither empirically nor in detail. A general assumption is that an original metaphorical idea may start out as a suggestive hypothetical interpretation of the data at hand, and then gradually be clarified either within in the same article or by other researchers of the community. This process of clarification and scrutinizing of the actual meaning and of the exact range of the metaphor is twofold: the metaphor can be either explained experimentally or expanded conceptually.

A metaphor consists of three elements: (a) the topic, which is the phenomenon we want to say something about, (b) the vehicle, which is the phenomenon we are using in doing so, and (c) the specific and relevant instances of comparison taken place. In the metaphor "hitchhiking genes," the topic is the specific types of gene; the vehicle refers to the hitchhiking activity. The specific instances of comparison between the two phenomena could be "ability to move" and "ability to take others with you as you move" whereas other instances like "risky behavior" are absent from the metaphor, though perhaps theoretically possible.

In *explaining* the metaphor, the topic is studied scientifically and the specific relevant instances are identified. In studying protein synthesis, which is the case in this article, experimental testing of various kinds is the favored approach. By scrutinizing the metaphor experimentally, it gradually becomes less of a hypothetical metaphorical idea and more of an established concept with metaphorical origins. The meaning of such a conventional metaphor will at some point be settled and almost literal, having identified the relevant comparisons and disregarded the rest. Some conventional scientific metaphors even merge with the original vehicle term. As a result, this term will have become polysemous and simply included the former metaphorical reference into the definition of the term. Several metaphors have in fact been used to describe this process of conventionalization: we talk about "dead" metaphors, "frozen," "crystallized" and "hardened" metaphors contrasting "living," "fluid" and "open" ones. Whichever terminology one prefers, they all depict something flexible turned inflexible to describe how original ambiguity as to the scope and exact meaning of the metaphor has been settled. In the present study, I use the distinction either novel/conventional or open to interpretation/closed to interpretation.

Secondly, innovative scientific metaphors may be *expanded conceptually* by spinning off more metaphors. For instance, the metaphor of "the genetic code" kicked off several related metaphors such as "genetic translation," "words," "genetic reading," "transcription," "making sense," "making nonsense," "dictionaries," "libraries" and more (Knudsen, 1999).

The metaphor immediately following the introduction of "the genetic code" was constructed as an answer to the question: "*In what way* is protein synthesis a genetic code?" The answer was: "It *translates* messages between nucleotides and amino acids." The metaphor of the genetic code became a root-metaphor and expanded from one single metaphor ("protein synthesis is a code") to an entire network of several interrelated metaphorical expressions.

"The career" (Gentner et al., 2001) of scientific metaphors in developing from single and often hypothetical ideas to a network of related, conventional and well-defined metaphors has rarely—if ever—been studied empirically. The concept of metaphor is used not only to generate new understandings, but also to express these new insights (Black, 1962: 33) or in "giving voice to particular kinds of data" (Keller, 2000: 76). Consequently, we still don't know much about how the multiple, potential meanings (instances of comparison) of a given metaphor are resolved and communicated. Though analogical and metaphorical reasoning can be understood as cognitive and cultural processes, scientific metaphors have to be transformed from ideas into language (though not necessarily expressed figuratively) in order to be developed at all. To be communicated, negotiated and conventionalized, they have to be used in actual texts. So, in studying metaphorical development, textual analysis of the texts in which this development takes place seems a sensible solution. However, there is a problem in doing so. Even though the exact meaning (the specific instances of comparison) changes over time owing to explanation and extension processes, the metaphorical expression is likely to remain the same. Somehow, the texts must signal whether the metaphor is supposed to be understood as a figurative hypothesis or a formerly figurative concept. This article presents the results of a study of the changing form and usage of metaphors, using the root-metaphor of "the genetic code" as the case. This metaphor was introduced in 1944 into the international molecular biological research community in order to describe and understand the process of protein synthesis. About 20 years later, the code had been broken, and the open metaphor of the code had given rise to a cluster or a network of more or less conventional metaphors. This study is focusing in particular on the role of scientific and popular scientific genres in the development process, and the changing strategies in communicating the developmental stage of the metaphors.

Communicating novel and conventional metaphors.

On the basis of studies of the cognitive process of understanding metaphors, Gentner et al. (2001) introduce "the career of metaphor hypothesis," indicating that the exact meaning of novel metaphors is created through a process of actively aligning elements between a topic and a vehicle. In contrast, the meaning of conventional metaphors is only associated with the vehicle and no alignment process is necessary. So, if a scientist were to understand the novel metaphor "genetic translation," she would have to actively mix aspects of linguistic translation with aspects of cellular activity in order to construct meaning. After years of research, "genetic translation" would have settled terminologically, and the term "translation" would simply have acquired two separate conventional senses: linguistic translation and genetic translation. So, as the metaphor grows more conventional, a shift in cognitive processing strategies from comparison *between* domains to categorization *within* domains takes place.

Furthermore, Gentner et al. find that novel metaphors are preferred in the form of similes. People even tended to consider similes more metaphorical (that is more open and suggestive) than traditionally expressed metaphors. This is probably because similes explicitly identify an expression as figurative by including comparative words such as "like" or "as." The explicit inclusion of these words signals that an alignment process should take

place. Correspondingly, conventional metaphors should invite the traditional metaphorical form, because the meaning is pre-stored and well-known and constructing meaning no longer relies on active alignment between categories. As a result, a research question of this study concerns the metaphorical form, and whether novel and conventional metaphors might be expressed by similes or metaphors.

Another research question concerns the text surrounding the metaphors. According to relevance theory (see among others Sperber and Wilson, 1986; Wilson and Sperber, 2004), readers are capable of employing several inference strategies when processing novel concepts (metaphorical and non-metaphorical concepts alike) enabling them to comprehend new or unexpected terms. Consequently, a reader of a scientific text will possess inference strategies in order to be able to interpret novel metaphors in scientific discourse, even though they are not pre-stored or otherwise established. This interpretation is not necessarily identical with the one intended by the writer, but simply one that enables the reader to make sense using the information available to her at the time. Since novel metaphors are in nature open to interpretation, the writer might want to push the reader in the right direction by incorporating some kind of ostensive stimulus; that is by adding textual markers attracting attention and focus to the intended meaning. Successful scientific communication relies on the intended meaning of concepts being communicated precisely, clearly and convincingly, so when applying novel metaphors we might expect authors to provide the reader with help in resolving—or reducing—the intended meaning of the metaphor.

However, the reader needs more than that. In line with relevance theory, Goddard (2004) argues, that in order to fully comprehend a novel metaphor the reader will need some form of broadly understood meta-linguistic awareness. In other words, in order to interpret a novel metaphor as intended, the reader needs to be made aware of the fact that the metaphor is indeed a metaphor. Explicitly identifying the metaphor as a metaphor would be the most obvious and ostensive way of securing the reception of the metaphor, but explanations and paraphrase might serve the same purpose. A conventional metaphor has become part of the scientific lexicon of the article, and will no longer be in need of additional ostensive stimuli in order to be comprehended as intended.

So, in identifying a given metaphor as either novel or conventional, it is relevant to analyze the immediate linguistic contexts of the metaphor and the linguistic strategies used to secure or anchor the intended meaning of the metaphors. These strategies will probably change during the career of the metaphor in the sense that the ostensive stimuli used to identify the metaphor as indeed a metaphor and the need to control or guide the interpretation will gradually disappear.

2. The case study: material and method

The genetic code as a network of interrelated metaphorical expressions

Experimental and theoretical research in understanding the mechanism of protein synthesis was taking form during the mid-1950s, and the mechanism was finally established in about 1962. The metaphor of the genetic code is more precisely a network of related metaphors all referring to "the code" as a central root-metaphor. Following the invention of the metaphor, several other metaphors were generated in order to elaborate and clarify the initial metaphor.

Construction of text corpus

In order to study the development of the metaphor, I constructed a corpus consisting of the most influential research articles in researching protein synthesis. Constructing the material for this study proved to be something of a quilting process, and I applied three strategies in piecing it together.

The Science Citation Index was searched in order to become acquainted with the size of the field and to discover citation superstars (Harmon, 1992) within the field. Articles were selected on the basis of their reference to protein synthesis or the genetic code in their titles and abstracts. I included the non-figurative term "protein synthesis" as a search term, because the possibility of code-related metaphors in these articles was considered high. The first entrance in the Science Citation Index is 1944–1955, so we don't have the exact data before that. This search revealed only a few articles using metaphors related to the code metaphor before 1960, but the number was growing rapidly, and the amount doubled from the period 1960–1962 to the period 1963–1965. Articles containing the non-figurative term "protein synthesis" in the title or abstract also increased dramatically from 1955 to 1965. The number of articles published grew from 41 involved articles on average per year in the late 1950s to an average of 181 articles per year in 1965.

A second strategy was needed to make sure the corpus included influential texts not registered in the Science Citation Index. In doing so, I was dependent on works on the history of science and biology (e.g. Olby, 1994; Cantor et al., 1990; Judson, 1979; Mayr, 1982; Gribbin, 1985; Kay, 1997, 2000). I also traced the references of these famous articles referred to in these books. Both strategies revealed a number of texts and genres the Science Citation Index could not account for such as chapters in books, lectures, review articles published in anthologies and popular scientific texts.

Having identified the central and canonic texts of the development of protein synthesis, I selected a corpus including only articles actually employing metaphors of the genetic code somewhere in the text. Since the aim of this study was to understand how novel and conventional metaphors are communicated and not how often these metaphors are applied, the exact density of metaphors was not relevant. A total of 175 texts explicitly using the metaphor and 1,006 articles referring to "protein synthesis" were collected as a start (Table 1).

The final corpus was constructed from this collection of texts. Since the appearance of the metaphor in the early texts was scarce, I included more or less all available texts from the period, which amounted to one book from 1944 and 22 articles published between 1954 and 1960. After the breakthrough in late 1961, the metaphors became much more commonly used, and I selected the 10 most cited texts published in 1961, 1962, 1963, 1964 and 1965. As a result, the corpus used in the analysis consists of a total of 70 articles and chapters.

Table 1. Metaphor references

Period	References to the code metaphor in title or abstract	References to protein synthesis
1941–1945	0	0
1946–1950	0	100
1951–1955	2	
1956–1960	20	238
1961–1965	153	668
Total	175	1006

When I began this study, I intended the corpus to include only specialist research articles. The majority of the texts are just that, but to my surprise it turned out that very influential texts in the development were not all standard research articles. Some of these texts are genuine popular scientific texts intended for a larger audience (though still not everyman), while others are non-experimental, theoretical or review articles published in distinguished scientific journals such as *Science*, *Nature*, *Proceedings of the National Academy of Sciences* and *Journal of Molecular Biology*. Even though standard specialist research articles are generally considered to be the primary genre of communicating novel scientific ideas and research, more popular scientific genres apparently play a significant role in scientific innovation as well. Schrödinger's *What is Life?* is a unique, but excellent example, because it succeeded in presenting protein synthesis as a puzzle, or a riddle to be solved, while at the same time providing the tool for solving this biological problem: namely physics. These popular and even textbookish texts are included in the corpus.

Analyzing metaphor

In identifying the metaphors of the texts I have applied Lynn Cameron's definition of metaphor:

> A stretch of language in its discourse context is said to be a linguistic metaphor if it contains a reference to a Topic domain by a Vehicle term (or terms) and there is potentially an incongruity between the domain of the Vehicle term and the Topic domain. (Cameron, 1999: 18)

This definition works very well in identifying metaphors in which the difference between the vehicle term and the topic term is substantial. However, when this difference between the terms is less substantial, it becomes more difficult to decide whether a given expression counts as a metaphor or not. An example is the metaphor of "genetic information." The idea of a genetic code originates in the assumption that the organism, the cell and the DNA/RNA contain "information" or "messages." If "information" is categorized as a communicative or linguistic phenomenon, the application of the term "information" in biology should be considered metaphorical. But if "information" derives from information theory, it is defined more generally as simply a sequence of things, and will be applicable to biology non-figuratively. In this article, "genetic information" is classified as a metaphor, because several early texts treated it as a metaphor in need of explanation and illustration, but we are talking about a borderline case.

Cameron's definition does not distinguish between the various linguistic forms, and genuine metaphors, similes, quasi-similes, analogies, and personification all count as metaphorical. Since this study focuses specifically on linguistic communicative strategies, I will briefly introduce the types of metaphorical expressions, bearing in mind that demarcations between these types in this list are actually quite fuzzy in real life:

Explicit metaphor	A metaphorical expression explicitly identifying the vehicle with the topic (the A *is* B-form. Example: "Protein synthesis *is* a code")
Implicit metaphor	A metaphorical expression in which only the vehicle is present in the text (the B-form. Example: "The code")
Simile	A metaphorical expression explicitly comparing the vehicle and the topic stressing similarity (the A *is like* B-form. Example: "Protein synthesis *is like* a code")

Quasi-simile	A metaphorical expression more implicitly comparing the vehicle and the topic stressing similarity, but using another connector than "as" or "like" (A *can be considered to be like* B; A *is called* B. Example: "Protein synthesis *could be regarded as* a code")

The following study of texts falls into two parts. The first part presents the birth of the metaphor between 1944 and 1954, as it was introduced into the discourse as a novel metaphorical expression of an innovative and strongly suggestive idea. This section also serves as a short introduction to central components of the metaphor network. The further development of the metaphor falls into two stages. The first stage, between 1954 and 1960, is the developing period in which the metaphor is researched, and the amount of involved metaphors rises. The period between 1961 and 1965 was a period of establishment, in which the meaning of the metaphor expressions settled and became conventional. The second part of the analysis presents this process by comparing the strategies in communicating the metaphors during these two periods.

3. The early years and the introduction of the metaphor of the code

The ideas of biological messages and of inheritance of such messages were born in the nineteenth century, but the actual metaphor of the genetic code grew out of the context of World War II and the Cold War and related practices and technologies such as cryptoanalysis, decoding messages, the invention of early computers and the introduction of physics in biology (Kay, 1997). Keller (1995: 81) points to the complex system of the telegraph and of information transfer as the dominating images in most biological thought, contributing to the dominating "discourse of information":

> In the 1950's molecular biology underwent a striking discursive shift: it began to represent itself as a communication science, allied to cybernetics, information theory and computers. Through the introduction of terms such as *information*, *feedback*, *messages*, *codes*, *alphabet*, *words*, *instructions*, *texts*, and *programs*, molecular biologists came to view organisms and molecules as information storage and retrieval systems. Heredity came to be conceptualized as contemporary systems of communication, guidance, and control. This linguistic repertoire was absent from molecular biology before the 1950s. (Kay, 1997: 25, emphasis in original)

The metaphor of the genetic code describing molecular biological processes was published for the first time by the physicist Erwin Schrödinger in 1944 in his popular scientific book *What is Life?*. Schrödinger presents the metaphor as an intriguing research hypothesis or even a modern quest:

> It is these chromosomes that contain in some kind of a code-script the entire pattern of the individual's future development and of its functioning in mature state. Every complete set of chromosomes contains the full code; so there are as a rule, two copies of the latter in the fertilized egg cell, which forms the earliest stage of the future individual. (Schrödinger, 1944: 21)

Notice that both vehicle (code-script) and topic (the entire pattern of the individual's future development/chromosomes) are represented in the text, but the exact reference—the DNA—was still unknown to Schrödinger at the time (though it was later argued that he really should have known better (Pauling, 1987; Perutz, 1987)). The following passage extends the metaphor by elaborating or pointing out the central attributes of the metaphor. The topic is

now represented in the text as "the structure of the fibre," and it is this idea of structure, that seems to be the center of comparison between the code-script and the chromosome:

> In calling the structure of the fibre a code-script, we mean that the all penetrating mind . . . could tell from their structure whether the egg would develop, under suitable conditions, into a black cock or into a speckled hen, into a fly or a maize plant, a rhododendron, a beetle, a mouse or a woman. (Schrödinger, 1944: 21)

The metaphor is pointed out as metaphorical by ostensive signals, pointing to the fact that the expressions are not intended as literal, and also pointing out how they should be interpreted. In the previous example this is done by explicitly being tentative, vague or suggestive: "in some kind of code-script"—and in the second by identifying the metaphor as a name or a label signaled by the phrase: "In calling A for B . . .," and subsequently illustrating the metaphor. When the metaphor is repeated at the end of the chapter, these ostensive signals are still used; in this case by explicitly defining the expression as figurative ("a simile") and by paraphrasing the metaphor:

> But the term code-script is, of course, too narrow. The chromosome structures are at the same time instrumental in bringing about the development, they foreshadow. They are law-code and executive power – or, to use another simile, they are architect's plan and builder's craft – in one. (Schrödinger, 1944: 22)

Since the structure of DNA had not been fully understood, the metaphor rested for a decade until it was reinstated by another physicist, George Gamow (1954). Gamow presented his version of a genetic code understood as a translational relationship between DNA and protein. This idea was directly inspired by Watson and Crick's model of DNA published in 1953 promoting the structure of the DNA molecule as a long sequence of letters containing genetic information (Watson and Crick, 1953). Gamow extended the original code metaphor, by specifying the coding relation between DNA and protein as a relation of translation:

> Thus the hereditary properties of any given organism could be characterized by a long number written in a four-digital system. On the other hand, the enzymes (proteins), the composition of which must be completely determined by the deoxyribonucleic acid molecule, are long peptide chains formed by about twenty different amino acids, and can be considered as long "words" based on a 20-letter alphabet. Thus the question arises about the way in which four-digital numbers can be translated into such words. (Gamow, 1954: 318)

These novel metaphors ("a long number," "long 'words,'" "a 20-letter alphabet," "can be translated") are identified and communicated as figurative in two ways: first by using the form of a quasi-simile ("hereditary properties . . . could be characterized by a long number" and "twenty different amino acids . . . can be considered as long 'words'") and second by using inverted commas when talking about "words." In a succeeding paper published in 1955, the metaphors and the strategies in communicating them as metaphors are repeated almost verbatim.

The construction of metaphors during the early years is hypothetical, thus preceding experimental evidence. Schrödinger and Gamow suggested experimentally unfounded metaphors, but these metaphors seemed to be suggestive and inspirational anyway. This developmental pattern of metaphors preceding experimental evidence exists in other cases as well. Cyrus Levinthal wrote in 1959 about the idea of what was later to be known as "cellular transcription" and "translation":

There is, as yet, no direct evidence that this model is correct, but it is interesting to note that the adaptor hypothesis was made two years before there was any chemical information on the attachment of amino acids to soluble RNA. (Levinthal, 1959: 250)

Experimental evidence, then, verifies, adjusts or challenges the metaphor. Gamow's metaphor of a translation mechanism between numbers and words caught on, but the molecular biological details did not fit the chemical knowledge at the time. Protein synthesis seemed to be a two-stage process rather than the one-stage process suggested by the translation metaphor, and Gamow had to reconsider his metaphor of translation:

This negative result is presumably due to over-simplification of the original picture, since it seems, indeed, that the transfer of information from chromosomes to enzymes is a two-way process. First the information stored in DNA molecules are transmitted to the molecules of RNA (Ribonucleic Acid) which move out into the cytoplasm of the cell and form the so-called microsomes. (Gamow, 1955: 1)

The problem was not the metaphor as such, but whether DNA or RNA is the agent in the translation. In yet another article from 1956, the metaphorical expression (vehicle) is repeated, but the topic is re-interpreted. Consequently, the meaning of "translation" is re-established as a process between DNA and something else ("elements") which then again determine the composition of the proteins (rather than describing one direct transformational process between DNA and protein).

It seems that metaphors may be used in scientific discourse as hypotheses, but if they are challenged by experimental data, the community refrains from using them. Even though the reformulation might seem perfectly valid to outsiders, the metaphor does not appear in the discourse before the two specific processes had been experimentally verified. Alternatively, when the relationship between DNA/RNA and proteins was discussed, the authors would use less specific words such as: nucleic acids "manufacture" amino acids; the nucleic acids of the template "correlate" to a corresponding protein; nucleic acids "determine" the amino-acids; they have "a relation"; they have "interactions" or they "specify" the proteins. These words replaced the metaphor of translation until 1961, when it was formally reformulated as part of the larger code metaphorical network again along with the metaphor of "genetic transcription."

4. Developing scientific metaphor

From multiplicity to uniformity of genre

Research in the mechanism of protein synthesis between 1955 and 1960 was characterized by construction of new theoretical ideas and concepts. Some of the most influential metaphors were published during this period, but further development often stranded because of lack of experimental evidence. "Working hypotheses are slowly taking shape, but the experimental facts are few" seemed to be the verdict around 1958 (Chantrenne, 1958: 49). During this period the genres in which the metaphors appear fall into two categories, existing side by side:

- Predominantly theoretical texts reviewing and interpreting the nature of the code without actual presentation of original experiments (though the texts refer to experimental research of others). This group includes more popular scientific genres.
- Standard experimental research articles reporting original research and experimentally based biochemical methods and results.

The status of the research as theoretical or tentative is highly emphasized in the articles, and the proposed ideas, metaphors and mechanisms are often communicated with reservations and uncertainties, as in the following example:

> Many of these ideas are highly speculative and should be thought of only as current working hypotheses (or dogmas) which are being subjected to experimental tests . . . It should be stressed, however, that there is no direct evidence in support of this assumption, nor can a precise mechanism be formulated at present, which might explain how the required bonds would be made. One only can speculate . . . (Levinthal, 1959: 249)

These texts reveal a high awareness of how strongly claims and conclusions can be presented. Since the claims and ideas represented in these texts are theoretical and not necessarily backed up by experimental research, the hypotheses and interpretations are weak and tentative. Authors suggest that these theoretical considerations "may perhaps be of significance" (Crick et al., 1957: 419), while identifying areas in need of further research. The general aim of the texts of this first category is to explain and review current research and to provide theoretical interpretation of experimental results. Consequently, the proportion of metaphors used in these texts is rather high, and the metaphors are used to express hypotheses. However, while modestly acknowledging gaps of knowledge, the texts simultaneously shape the entire research field of protein synthesis by interpreting existing research within a general framework of the genetic code and by explaining data and results through the specific metaphors. These theoretical texts discuss several metaphors repeatedly, thus representing the first step in the establishment of the network of metaphors of the genetic code.

In relation to the theoretical interpretations and explanations, the second type of text presents the experimental research. While the theoretical papers aim at explaining the entire system by presenting several interrelated metaphorical expressions, the more standard experimental articles have a much smaller scope, in the sense that they present specific biochemical problems and experiments rather than ideas. In these texts, the metaphor of the code is used as a point of reference or title indicating the wider perspective, relevance or general implications of the specific experiments. Consequently, the application of actual metaphors is restricted to a reference once or twice in the introductory or concluding paragraph of the article.

After the breaking of the code in late 1961 (Jacob and Monod, 1961; Nirenberg and Matthaei, 1961), the theoretical genre including popular scientific texts no longer played the same role in seriously developing and interpreting the metaphorical framework. The frontier had changed, and now basically chemical answers were needed. Thus, the genres in which we find the metaphors of the genetic code change compared to the early years. The popular scientific texts are no longer represented in the frontline of researching texts. This is not because such popular texts do not exist, but because they no longer play the same role in the conceptual development. Some of them are cited in experimental research, but not to the degree they used to be.

With the exception of certain metaphors (such as "the messenger" and "messengerRNA"), the textual pattern of metaphor application in specialist research articles during this period remains more or less similar to the pattern in the early research articles. The metaphors provide the frame of reference of the research and they set the scene, while the biochemical experiments, methods and results represent the specific focus of the research. Except for a few examples, the metaphors are still mainly used in the introductory and the concluding sections of the articles, and the material/method and results sections are

reserved for communicating more biochemical concepts and processes. This tendency grows stronger over the years, and in 1965 code metaphors are exclusively used in introductions and conclusions.

From two separated discourses to one integrated

During the early years, a metaphor would seldom appear in the texts unaccompanied. When a metaphor was introduced, it was also explained or defined. This explanation could take two forms: it might be explained biochemically or metaphorically or by a combination of the two strategies. For instance, when Gamow introduced the generative metaphor "genetic translation" explaining the kind of code protein synthesis could be said to be an example of, he also introduced an entire metaphorical universe in which the metaphor of translation would make sense. In the following example, you can see the process presented within a metaphorical linguistic/communicative universe and in the parentheses the story you will find has the same elements repeated in biochemical terms:

> Mathematically, the problem reduces to finding a procedure by which a long number written in a four digital system (four bases forming the molecules of nucleic acid) can be translated in a unique way into a long word formed by twenty different letters (twenty amino acids which form protein molecules). (Gamow, 1955: 1)

The same phenomenon is represented in two forms in the same text: a metaphorical and a more literal form—except for the metaphor of "translation," which cannot be paraphrased in biochemical terms. So, the role of these other metaphors is to provide some form of explanation or scaffolding for the central metaphor of "translation." In other words; a metaphorical and a biochemical discourse are represented simultaneously. Only the generative, irreplaceable metaphor of "translation" is part of both discourses, in the sense that no other biochemical terms exists to represent the specific process.

The emergence of an extensive metaphorical universe in these early texts is particularly interesting, because it means that the texts are filled with a lot of surplus, illustrative metaphors merely providing scaffolding for the truly important and generative metaphors. These scaffolding metaphors represent objects, while the generative theory-constructive metaphors represent relations between the objects. The scaffolding metaphors are represented only to explain the central metaphor, since they could be replaced by molecular biological terms. The metaphors of "digits," "words" and "letters" are paraphraseable (as "bases," "amino acids" and "protein"). In contrast, the metaphor of "translation" is not.

This pattern of using scaffolding metaphors and two discourses is representative of the early texts, but gradually the scaffolding metaphors disappear and the remaining ones become more and more incorporated into the texts as implicit metaphors. From early 1962, the metaphorical and the biochemical discourse have melted into one, in which the metaphors of the code are fully integrated into the molecular biological discourse. After 1963, they are used as transparently as any other conventional and established scientific concept—even in the introductory sections. The example below illustrates how metaphors such as "genetic information," "expressed," "transcription", "messengers," "reading" and "message" are fully incorporated into the text:

> Genetic information in DNA is apparently expressed via transcription into RNA messengers which in turn act as templates for protein synthesis. Thus, incorporation of base analogues into messenger-RNA could lead to errors in the reading of the message into an amino acid sequence. (Champe and Benzer, 1962: 532)

In general, any form of explanation, paraphrase or just mentioning of the topic element of these metaphors dies out. The vehicle and the topic of the metaphor may be represented in the same sentence or paragraph, but they are not explicitly connected. The tendency of implicitly paraphrasing the metaphors also decreases during the run of the period: in 1963 seven out of ten articles implicitly paraphrase one or two metaphors; in 1964 three metaphors were implicitly paraphrased just once in the ten texts; and in 1965 it happens only once.

Marking the metaphor as deviant

During the developing period, all references to code metaphors stand out from the rest of the text by being marked as somehow different, being represented in either inverted commas or italics or by explicit reference to them as indeed metaphors or metaphorical comparisons:

> If quadruplets ("four letter words") are similarly used, there are 27 good "words" per code, clearly enough to encode all the amino acids that occur in proteins. (Beadle, 1960: 67)

> As a possible reason for the fine dispersion of nonsense might be the provision of "commas." (Crick, 1959: 36)

> We use the term "information" in the sense of a molecular specificity, that which distinguishes one protein from another. (Gamow et al., 1956: 66)

This behavior may in some ways resemble the typical introduction of any kind of disciplinary terminology in a text (metaphorical or not), but it is significantly different as well. The general rule in highlighting relevant terminology prescribes highlighting when the term is used for the first time in a text. In contrast, these metaphors are often highlighted throughout the entire text during the period 1955 to 1960, while very rarely being highlighted at all in later articles, not even in introductory sections. Following the period of establishment of the metaphor, the marking the metaphor as deviant gradually changes. After 1961 the amount of metaphors marked out as deviant from the literal, scientific language decreases dramatically. In 1961 and 1962, metaphors are still marked out occasionally, mainly because new metaphors are included into the metaphor network. In the example below, you can see how the three established metaphors "translation," "code" and "dictionary" are not highlighted, while the metaphor "word" is.

> The translation of a four-letter nucleotide code into a twenty-"word" amino acid dictionary has been the subject of much speculation. (Matthaei et al., 1962: 666)

This article is rich in metaphors, but "word" is the only highlighted one. The unmarked metaphors are established within the discourse at this point, while "word" has not become established as a scientific concept. In this article the authors focus on the amino acid words in particular, and the authors' aim is to present experimental research concerning the nature and specificity of these molecular words. In doing so, they are also re-defining the metaphor and particular types of amino acid words: the "nonsense" words:

> Coding units which would not direct amino acids into protein will be called "nonsense words". Up to now, it has not been possible to determine directly whether the code contains nonsense units. (Matthaei et al., 1962: 674)

In contrast, during the period 1963 to 1965 only six instances of inverted commas or italics marking metaphors are found in the entire material. During this period, metaphors of

the genetic code are not marked out as different in any way, indicating that they are now established within the discourse. Notice in the examples below, how the metaphors "message," "encoded," "readable" and "non-readable" are incorporated into the discourse:

> . . . the molecular weight of the message could be related to the size of the polypeptide chain which it encoded. (Staehlin et al., 1964: 264)

> Such considerations suggest that the sequences CpUpU and CpUpC may be readable internal codons for Leu-sRNA, but may be less efficient or nonreadable at a terminal position. (Bernfield and Nirenberg, 1965: 483)

In articles particularly aiming at discussing the molecular reality of a particular metaphor, the metaphor will in a few cases be highlighted, but in most cases it will not. However, entirely new metaphors presenting novel, original, and unestablished metaphors relating to the code are still highlighted in some form.

From similes to implicit metaphors

Using experimental data, Gentner et al. (2001) argued that similes were preferred over explicit or implicit metaphors in processing novel metaphors. This pattern is reflected in these articles as well, where similes and quasi-similes dominate the early texts. Here is an example in which a (biochemical) sentence is explicitly compared to a linguistic sentence and subsequently explained by using the comparative term "similar to." The following example illustrates a similar explicit comparison between difficulties in breaking a biological code and a military one. The authors suggest similarities between vehicle and topic, but not total identification:

> The sentence is similar to that existing in any language where sensible sentences like: "Amino acids form proteins" or: "Read Alice in Wonderland" each containing 21 letters, represent only a negligible fraction of all possible sequences of the same length formed by the letters of the alphabet. (Gamow et al, 1956: 40)

> We face here difficulties similar to those encountered by an Armed Force's Intelligence Office trying to break an enemy code on the basis of a single message less than two printed lines long. (Gamow et al, 1956: 40)

In the early texts, both topic and vehicle are represented together, and introductory similes are often taken up later in the text in the form of implicit metaphors combined with explanation or paraphrase. These various strategies of controlling the interpretation of the metaphor by representing both topic and vehicle in the text indicate that the metaphors have not yet become established within the discourse, much less become non-metaphorical scientific concepts. In contrast, the almost exclusively preferred figurative form from 1962 and onwards is the implicit metaphor. Similes and quasi-similes are out of the picture.

Neither early nor later texts use standard explicit metaphors in which a vehicle and a topic are identified with each other by the use of some form of the verb "to be." The early texts use none at all, and in the later texts only very few instances of explicit metaphors can be found.

The authors have very good reasons for disregarding explicit metaphors. When dealing with truly generative metaphors, a more appropriate, biochemical term simply does not exist. No other term representing the process of biochemical translation, for instance, is available (otherwise the metaphor wouldn't be needed at all). In cases where such expressions of the topic take place, it would be essentially untrue to postulate that for

instance a word and a certain biochemical molecule were literally identical. Proteins are not literally words, but they sometimes act as though they were—and the expression should be able to communicate this difference. Cases in which an explicit metaphor might be useful (for instance when introducing the metaphor of "biochemical words") are resolved by the use of a quasi-simile or an explained implicit metaphor. A popular strategy is to use an implicit metaphor in one sentence and the non-metaphorical representation in the next. The vehicle and the topic are then both represented within the same paragraph, but they are not explicitly identified.

5. Conclusion and discussion

The role of popular scientific genres in generating innovative metaphors

During the period, the metaphor swings between needing biochemical and conceptual-metaphorical clarification. It is interesting to note that a lot of the conceptual and metaphorical development takes place in popular scientific genres and texts (such as popular lectures, textbooks, review articles and popularizations) while the standard research articles mainly deal with experimental clarification of the metaphor. The authors cite each other independently of genre. Sometimes the scientists even publish within both genres, but the two kinds of development of the metaphors are clearly divided between the two genres. When the metaphor is represented in research articles, it is mainly setting the scene and thus providing a theoretical frame of reference. This pattern remains, until the topic has been sufficiently and experimentally identified and established. Then the metaphor is included in the research article as a scientific concept, and here it probably remains as long as it serves a scientific purpose.

The fact that metaphors enter the standard research article does not mean they were not used in popular scientific texts. They certainly are, but following the establishment of the metaphor within a restricted, experimental context, the popular genres no longer play the same role as a scene for innovation. Whether this pattern is general for the application and function of metaphors in scientific communication is difficult to say, but it would not be a totally unlikely scenario. Creating and developing deeper and more structurally rich metaphors takes a broader disciplinary perspective than what is usually involved in the more focused presentation of research results in standard research articles. In order to take the more universal perspective needed in creating and exploring a substantial metaphor, the scientists need a genre in which a larger perspective would be in order and in which a larger set of experimental results were to be interpreted and communicated. This situation is at hand when writing textbooks, popular scientific articles or review articles, in which the specific task is to identify central scientific narratives and to have the individual research fragments make sense. Writing within these genres presents an ideal situation for the creation of metaphor, as both the genre invites them and the writing specialist approaches the task with a mind prepared for identifying the larger picture.

Communication of metaphoricity: from ostentation to invisibility

Novel and conventional metaphors are represented markedly differently in scientific articles. Textual strategies in communicating metaphors change as the metaphors are being researched experimentally and thus established into the discourse. Novel metaphors are much more explicitly present in the texts as figurative; by being typographically marked out as deviant, by being explicitly identified as figurative and/or by taking the form of simile thus

clearly emphasizing comparison between two elements of two otherwise distinct categories. In contrast, conventional metaphors are integrated into the biochemical discourse and as such much more invisible as metaphors. Whereas novel metaphorical ideas are explained, paraphrased metaphorically and biochemically, conventional metaphorical concepts are explained biochemically, if they are explained at all. So, the more unprotected, unexplained and integrated into the biochemical discourse the metaphors are, the more established and conventional they will be. Simultaneously, this study finds that the less the need of metaphorical scaffolding (surplus, illustrative metaphors), the more established the metaphors will be. When metaphors are new and tentative, unexplored and open to interpretation, they are explained immediately.

The content of the articles grows ever more specific and biochemical in focus. Even though conventional metaphors are fully integrated and allowed entrance to the experimental research articles, their appearance is still primarily restricted to introductory and concluding sections. They are mainly used to provide perspective and interpretation of the biochemical processes researched in the articles. The experimental work is presented in a much more biochemically detailed scale even when the author is researching processes such as translation or transcription. The only noticeable exception is "the messenger" or "messengerRNA" describing specific instances of RNA. In general, the amount of metaphors in the articles decreases during the period of establishment. The same metaphor may be used repeatedly in the later period, but the variety of metaphors in a given text is limited. The scaffolding metaphors, frequently applied in the early texts, have disappeared, and only the generative metaphors representing biochemical relations between objects remain.

Discussion: from metaphor to fact and back again?

Conventional and established metaphors may be polysemous, but are they also literal? Is the creative power exhausted, has the metaphor lost its drive? Well, not necessarily, because this conventionalization is only established within a specific scientific context and this literal understanding is highly context-dependent. A newcomer to the specialized discourse of molecular biology might still need a metaphorical interpretation of the term "translation" initially, before gradually being socialized into the "proper" conventional interpretation and use of the concept. To her, it might still be a metaphor. In this discussion section, I want to put the developmental pattern of scientific metaphors into perspective by presenting two situations in which an otherwise conventionalized metaphor might be re-opened as truly metaphorical: in popular scientific texts and in texts in which the meaning of the metaphor is challenged.

The present study revealed the central role of popular scientific texts in innovation and theory-construction. The impact of these genres is gradually reduced following the experimental back-up and conventionalization, but they do not stop using metaphors. These metaphors, however, are used to communicate established ideas rather than generating ideas and promoting a communal interpretation of the metaphors. A case study of the metaphor usage in popular scientific texts from *Scientific American* following the establishment of the metaphor network of the genetic code (Knudsen, 2003) illustrates how otherwise conventionalized metaphors are presented in the texts as metaphors rather than established concepts. The strategies in communicating these metaphors are almost identical with the strategies used in suggesting a novel metaphor in a specialist context. Whereas the conventional metaphors are invisible as metaphors in specialist scientific texts at the time, the ones used in the more popular scientific texts are much more visible. They are clearly

highlighted as strangers by using quotes and italics, and by a preference for using figurative terms in the simile form.

Secondly, the popular texts apply many more metaphors than the specialist texts do. One reason for this increase is the reappearance of the scaffolding metaphors such as "letters" and "numbers," "sentences" and "writing." In contrast to the conventionalized metaphors, these metaphors can be paraphrased and even replaced by non-metaphorical, biological terms. An obvious reason for this state of affairs is that so many new metaphors relating to the metaphor of the code have been constructed, and that the popular texts are aiming at telling the entire story rather than a mere fragment. As in the early specialist texts, the involved metaphors are introduced with reference to their function within an entire metaphorical network. The following example illustrates how "the genetic code" is explained by including related metaphors such as "dictionary," "translate" and "language":

> The genetic code is not the message itself, but the "dictionary" used by the cell to translate from the four-letter language of nucleic acid to the 20-letter language of protein. The machinery of the cell can translate in one direction only: from nucleic acid to protein but not from protein to nucleic acid. (Nirenberg, 1963: 80)

When otherwise conventional metaphors are transformed from one context to another, their function changes simultaneously. Even though they look very much like novel and generative metaphors, they are not, because at this place in time they can in fact be paraphrased and replaced by biochemical terms. When the metaphor of "translation" was introduced in 1954, it was catachrestic and unparaphraseable, because the biochemical reality of the term had not been fully understood. "Translation" was a hypothesis, a tentative explanation of what might take place in protein synthesis. In the mid-1960s the definition of the term was clear. When these metaphors, established within a scientific context, are used as if they were novel metaphors, it is because the role of the metaphors is pedagogical rather than idea-generative. In this sense, the conventional and established metaphors are not entirely literal and clear-cut, because their metaphorical history is still alive somewhere and can be brought back and reused whenever the need for illustration of the processes of protein synthesis is required. So, even though these metaphors have been established and con-ventionalized for 40 years now, all the scaffolding, the illustrative metaphorical universe with its " words" and "sentences" still springs to mind when the metaphor is in need of explanation—even today.

Established metaphors are also open for re-opening and re-interpretation, if, for instance, new data put the content of the metaphor up for debate. This may describe certain aspects of a more current debate on genetic information versus genetic communication, in which it is debated whether genes are merely transferring information from the DNA/RNA to proteins, or whether in some instances RNA is communicating new information to back the DNA:

> What has become more evident is that the spatial patterns that develop in embryos are not to be understood in terms of gradients of positional information that are read or interpreted by genes to give spatial patterns of gene transcripts and products which then determine states of cell differentiation and morphogenesis. Such a picture is both far too static and programmatic to fit the observations. (Goodwin, 1988: 151)

In the case of the genetic code, the attempts at re-interpreting the metaphors arise as a result of inspiration from other disciplines. To the molecular biological scientist of the twenty-first century, the original metaphor of the genetic code may be established almost beyond recognition as a metaphor, because it has frozen in a particular position more or less

since the mid-1960s. However, in other parts of biology—particularly in evolutionary biology—the metaphors of "information," "information flow" and "transcription" are re-opened thus allowing the scientists to criticize and re-interpret or even discard the metaphor. This debate also takes place in the same kinds of genres used to launch the genetic metaphor in the first place: theoretical review articles, serious and learned non-experimental texts, textbooks and anthologies not presenting original or previously unpublished research. The strategies of communicating this process of re-opening are exactly the same as the ones used during the original introduction of the metaphor into biological discourse. A common way of questioning and thus expanding a closed metaphorical scientific concept is by identifying it as "merely a metaphor." Griffith (2001) cites S. Sakar for arguing:

> . . . there is no clear notion of "information" in molecular biology. It is little more than a metaphor that masquerades as a theoretical concept and . . . leads to a misleading picture of possible explanations in molecular biology. (Griffith, 2001: 395)

In the scientific articles of the 1950s and 1960s neither the idea nor the implications of biological "information" and "messages" were questioned. The metaphor was rarely explained in context; it was merely accepted and applied as an implicit metaphor. So even though the metaphor of "information" was clarified enough to be agreed on and closed, it wasn't debated or tested experimentally as much as the other metaphors were. In the excerpt above, Sarkar re-opens the metaphor of information by using inverted commas and citing its status as a metaphor rather than a scientific concept in order to criticize the validity of metaphor. He is somewhat mistaken in his verdict, because the metaphor of information is not necessarily misleading, because it is a metaphor, but this specific metaphor may no longer be the best tool in our understanding of these cellular processes. As a tool, the metaphor worked more than fine in the 1950s and 1960s in generating an understanding of the function and mechanism of the genetic code. However, this tool may have become blunt or the job may have changed. One of the things that definitely has changed is the surfacing of experimental evidence from related biological disciplines, which points to processes not accounted for or explained by the traditional understanding of these specific metaphors.

In order to re-interpret the metaphor, it needs to be opened first and to be identified as indeed a metaphor:

> Awareness of our use of metaphor provides an escape hatch from the prison house of language, or at least lets us know how we are confined. Such awareness . . . enables us to see the metaphoric in what is taken as literal, an act of unmasking . . . (Brown, 1976: 25)

Having re-identified the metaphor as a metaphor, the scientist can either discard the metaphor because of its metaphoricity or because of it being an inaccurate one, or she can repair and re-interpret the metaphor, thus providing the concept with new meaning. The metaphor "information" is in fact referred to in some texts as an open metaphor, and this is done by the use of inverted commas, the incorporation of similes and quasi-similes, and the representation of both source and topic in the texts. Ho (1988) takes the debate a step further by adding novel metaphors to the conceptual biological metaphor of genetic information. The metaphor she adds takes the conceptual metaphor in a new direction, because they are metaphors taken from human interaction and communication rather than information theory and computer science:

> This involves all sorts of processes in which the soma "talks" back to the germline as part of the functional interactions between different levels within the organism or between the organism and the external environment. I would include (a) the large-scale

reverse transcription of processed RNA's into DNA and reinsertion into the germline genome; (b) the non-random changes in genomic DNA in certain environments which can become stably inherited in subsequent generations; (c) biased gene conversion with or without mRNA intermediate, which is based on hypothetical functional feedback to the genomic DNA. (Ho, 1988: 134)

A metaphor is never just a metaphor after all. The very same expression holds different status within the scientific discourse communities at different times, and this status or level of metaphoricity is reflected in the use of genre and language. The texts clearly signal whether the metaphors are considered to be novel and work-in-progress or whether they are closed and conventionalized. In this sense, a conventional and established scientific metaphor, almost a fact, not only may have originated as an open metaphor, but may be transformed back into one again.

Acknowledgement

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