BioSystems 128 (2015) 1–8

Contents lists available at ScienceDirect

BioSystems

journal homepage: www.elsevier.com/locate/biosystems

Review article

Hidden in plain view: degeneracy in complex systems

P.H. Mason [a,*], J.F. Domínguez D. [b], B. Winter [c], A. Grignolio [d]

[a] Woolcock Institute of Medical Research, University of Sydney, 431 Glebe Point Road, Glebe, 2037 NSW, Australia
[b] Experimental Neuropsychology Research Unit, School of Psychological Sciences, Monash University, Australia
[c] Cognitive and Information Sciences, University of California, Merced 5200 North Lake Rd., Merced, CA 95343, USA
[d] Section and Museum of History of Medicine, University of Rome "La Sapienza", viale dell'Università, 34a 00185 Rome, Italy

ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form 20 December 2014
Accepted 23 December 2014
Available online 24 December 2014

Keywords:
Degeneracy
Redundancy
Pluripotentiality
Complex systems
Immune system
Brain
Language

ABSTRACT

Degeneracy is a word with two meanings. The popular usage of the word denotes deviance and decay. In scientific discourse, degeneracy refers to the idea that different pathways can lead to the same output. In the biological sciences, the concept of degeneracy has been ignored for a few key reasons. Firstly, the word "degenerate" in popular culture has negative, emotionally powerful associations that do not inspire scientists to consider its technical meaning. Secondly, the tendency of searching for single causes of natural and social phenomena means that scientists can overlook the multi-stranded relationships between cause and effect. Thirdly, degeneracy and redundancy are often confused with each other. Degeneracy refers to dissimilar structures that are functionally similar while redundancy refers to identical structures. Degeneracy can give rise to novelty in ways that redundancy cannot. From genetic codes to immunology, vaccinology and brain development, degeneracy is a crucial part of how complex systems maintain their functional integrity. This review article discusses how the scientific concept of degeneracy was imported into genetics from physics and was later introduced to immunology and neuroscience. Using examples of degeneracy in immunology, neuroscience and linguistics, we demonstrate that degeneracy is a useful way of understanding how complex systems function. Reviewing the history and theoretical scope of degeneracy allows its usefulness to be better appreciated, its coherency to be further developed, and its application to be more quickly realized.
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Contents

1. Introduction

In scientific usage degeneracy refers to the idea that different structural arrangements lead to similar outputs, or, in other words, that structurally diverse system components perform the same function (Edelman and Gally, 2001). As such, degeneracy is a desirable characteristic of systems. For example, degeneracy has been implicated in making systems more robust and more evolvable (Joshi et al., 2013; Meyers et al., 2005; Tian et al., 2011; Whitacre, 2010; Whitacre and Bender, 2010). However, just like many scientific terms, degeneracy has a different meaning in everyday language, where it commonly denotes negative dilapidation. In this paper we argue that the lay meaning of degeneracy has allowed an important concept to go largely unnoticed and that, given the ubiquitous presence of degeneracy in natural and social systems, it therefore remains "hidden in plain view". We review

* Corresponding author. Tel.: +61 422 967 686.
E-mail address: paul.mason@woolcock.org.au (P.H. Mason).

http://dx.doi.org/10.1016/j.biosystems.2014.12.003
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fruitful applications of the notion of degeneracy to the immune system, the brain, and language, a culturally evolved system. Our aim is to bring a particular operational conceptualisation of degeneracy out of its narrow scientific usage and into a common scientific lexicon.

Degeneracy, once an 18th century theory of how species change (Lawrence, 2009), became associated with undesirable deviation, hereditary degenerative disorders, and even infectious diseases such as tuberculosis (e.g., see Johnson, 1898) in the nineteenth and early twentieth centuries (Lawrence, 2010). The negative associations proved long-lasting and today medical doctors still refer to harmful degradation as a "degenerative" condition. Negative conceptualisations of degeneration overshadow a useful concept of degeneracy that George Gamow (1904–1968) imported into biology from physics and mathematics through his involvement with the RNA tie club including Francis Crick (Mason, 2010). In quantum physics, degeneracy refers to a situation in which different measurable states correspond to the same energy level. In the 1950s, Gamow contributed to solving the coding problem of DNA by suggesting that different nucleotide sequences in DNA could code for the same amino acid (Crick, 1955). Since then, scientists have found extensive degeneracy in the genetic code (e.g., Alvager et al., 1989; Barnett and Jacobson, 1964; Frank, 2003; Goodman and Rich, 1962; Grantham, 1980; Gu et al., 2003; Jestin, 2010; Kurland, 1992; Luo, 1988; Mitchell, 1968; Reichmann et al., 1962; Sequeira-Mendes and Gómez, 2012; Weisblum et al., 1962, 1965). Recent studies of degeneracy in bacteria have shown that different synonymous codons that interact with ribosomal proteins at ranging levels of amino acid affinity allow organisms to adapt to environmental changes given different amino acid availability (Subramaniam et al., 2013).

The contemporary scientific usage of degeneracy thus refers to the variable pathways that can lead to the same outcome, or the ability of different structures to perform the same function. For example, different gestures can convey the same communicative message, different chemical pathways can be used to metabolise food, and different proteins can bind to the same molecules. Degeneracy is constructive for understanding how components come together to form a synergy (Kelso, 2009), and has been shown to be a vital property of evolutionary systems, because it plays a central role in their reliability, adaptability and robustness (Whitacre, 2010; Whitacre and Bender, 2010; Whitacre and Atamas, 2012). Having multiple different backup pathways is how living systems maintain stability over time and also how they change, adapt and evolve.

In general, scientists have overlooked the concept of degeneracy not only because of the term's dominant negative meaning but also, we would suggest, because degeneracy is predicated upon a view of causality as being manifold and distributed. Such a view underpins the idea of multiple arrangements yielding the same output. This view of causality clashes with a traditional scientific analytical approach that favors isolating single causes for a given outcome. Geneticists looking for a single gene for a given function or neuroscientists looking for the brain area responsible for a specific behavior are examples of biases that hide degeneracy from scientific models. Furthermore, technological and methodological limitations have until recently restricted researchers to investigate one structure and one function at a time.

Besides being difficult to study, degeneracy is often confused with "redundancy," another term that is used differently in everyday speech and science. In everyday speech, we often use the word "redundant" to refer to something that is unnecessary. To be made "redundant" at the workplace, for example, is to lose your job. In science, redundancy refers to multiple copies of identical structures that perform the same function (Fig. 1). In information theory, redundancy refers to the transmission of more information than is strictly necessary to decode a message (Shannon, 1948). In both cases, redundancy is generally something positive. For example, redundant encoding of messages is argued to increase the success of transmission in noisy conditions (Hailman, 2008). The fact that both redundancy and degeneracy are generally considered positive system characteristics in science makes them very confusable. In line with this, degeneracy is often confused with redundancy, or a type of redundancy sometimes referred to as partial or functional redundancy. For example, two different genes that code for the same function are often labelled redundant even though they may be at different sites, may have different expression patterns, or may be additionally involved in other biological functions. We believe such a case is more aptly described as degenerate. The case of structurally dissimilar components realizing a similar function ("degeneracy") needs to be kept distinct from the case of structurally similar components realizing the same function ("redundancy"). Systems that exhibit degeneracy are not fixed to singular outcomes. In this sense, degenerate systems are pluripotent. While a redundant system has a set function, degenerate systems are functionally plastic. Articulating the distinction between degeneracy and redundancy is important if we are to work out the basic organising principles of complex systems. Inexact lexicons, reductionist biases, historical trends, and technological limitations are all impeding an unrestricted engagement with degeneracy.

Contemporary research findings are progressively giving cause to challenge reductionist approaches. Researchers have been gradually uncovering heterogeneous pathophysiology in clinical conditions such as Alzheimer's disease (Lock, 2013), Huntington's disease (Domínguez D. et al., 2013), Parkinson's disease (Lewis et al., 2005), schizophrenia (Dumit, 2004), asthma (Boulet et al., 2015; Reddel, 2012), chronic obstructive pulmonary disorder (Hardaker et al., 2013; Timmins et al., 2012), and sleep apnea (Dempsey et al., 2014; Eckert et al., 2013), among others. The interindividual variability of these conditions has implications for therapeutic approaches (Wang et al., 2011; Wang et al., 2013;

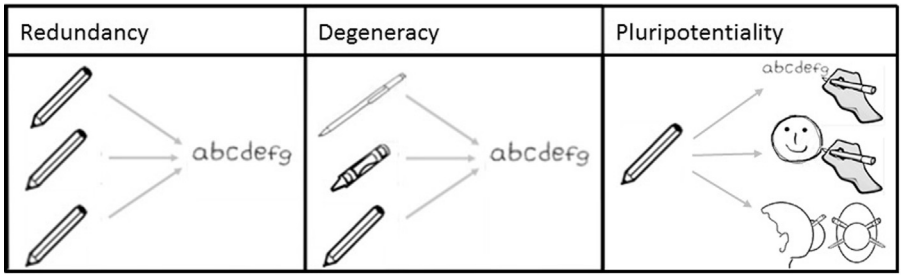

Fig. 1. Redundancy refers to identical structures, such as pencils, recruited for a similar task, such as writing. Degeneracy refers to nonidentical structures, such as pens, crayons, and pencils, recruited for a similar task, such as writing. Pluripotentiality refers to a structure, such as a pencil, being recruited for a selection of nonidentical tasks, such as writing, drawing, and as chopstick fashion accessories to hold hair in a bun.

Wong et al., 2014). Reifying, constructing, and sustaining a consistent and unified understanding of what are otherwise broad and fragile disease classifications is not only driven by reductionism, but also by political pressures to secure research funding (Lock, 2013). Forces internal and external to science have encouraged researchers to maintain the reductionist position, but this position is becoming increasingly untenable. Incorporating degeneracy into complex modelling allows researchers to move past reductionist shortcomings (Greenspan, 2012; Kelso and Tuller, 1984).

In the following sections, we review examples of degeneracy in immunology and vaccinology (Section 2) as well as neuroscience (Section 3). We then outline how the concept of degeneracy can be applied to cases that go beyond living systems (Section 4), using language as example. For each of these domains, we discuss cases that exemplify degeneracy, and we contrast this with redundancy and pluripotentiality.

2. Degeneracy in immunology and vaccinology

The concept of degeneracy found fertile ground in the field of immunology where it served as a wide-ranging explanatory concept. In the mid twentieth century, American immunologist Talmage (1959) hypothesized that different globulins could cross-react with a single antigen to make it possible for a limited number of immune cells to recognize countless environmental antigens, which Herman Eisen recognized as an instance of degeneracy ten years later (Eisen et al., 1969; Little and Eisen, 1969). Gerald M. Edelman further developed the concept of degeneracy within immunology, distinguishing two different operative levels: (1) the genetic level, where it manifests in the antibody-genes repertoire with the functional properties of specificity (i.e., the ability to react with some specific antigenic determinants and not with others) and universality (i.e., the ability to react against virtually any antigenic determinants) in antigen recognition; and (2) the level of organisms in biological populations, where degeneracy is regarded as a general evolutionary strategy to produce adaptability to unforeseen environments (Edelman, 1970, 1974). The reasoning drew upon an analogy between the selective mechanisms which play within the body (at a somatic level, i.e., among immune cells or neurons) and the ones operating in natural selection (among organisms).

The recent scientific literature in immunology regards degeneracy as a historical event in the context of antigen-antibody reaction (Cohn, 1994); as the "Yin and Yang of the immune system" for its pivotal role in T- and B-cell functions (Eisen, 2001); as a tool to design vaccines for treatment of infectious diseases (Gras-Masse et al., 1997; Wilson et al., 2004), including cancer (Schultze, 2002); as a conceptual frame to grasp the complexity of the immune system (Tieri et al., 2010) and to interpret bio-geographical individual adaptations of immune reactions (Grignolio et al., 2014); as a main property of the immune system similar to, yet different from, a series of concepts related to the one-to-many paradigm such as cross-reactivity (Cohn, 1994; Parnes, 2004), molecular mimicry (Bhardwaj et al., 1993; Damian, 1997), promiscuity (Larche, 1999; Burrows et al. 2003; Parnes, 2004; Wilson et al., 2004), and specificity (Sperling et al., 1983; Cohen et al., 2004).

In vaccinology, appearing as early as 1866, degeneracy carried its original and popular meaning expressing deleterious loss of "protective efficacy of vaccination" against smallpox. The basic idea was that the infective agent degenerates during "frequent" and "repeated transmissions" from animal to patient and from patient to patient, a process that in the long run, according to the then prevailing idea, "diminished its power [...], purity and strength" (Harding, 1866). For a century the alternate concept of degeneracy made its route through physics, molecular biology and immunology, and re-emerged in vaccinology to offer a new technical meaning based on the many-to-one logic to indicate that the flexibility of the immune system was based on T- and B-cell cross-reactivity.

To link degeneracy to versatility in immune function meant immunologists had to disentangle several dilemmas. First of all, that the world of antigens was far larger and more differentiated than that of antibodies. If T-cells were monospecific and did not exhibit degeneracy, a mouse, for instance, would require a lymphoid system 70 times larger (Mason, 1998). Similarly, it was essential to realize that B-cells also exhibit degeneracy, as suggested by the excess of globulin production for a specific antibody creation in response to immunization. Only until recently did vaccinologists start to consider these two phenomena in drug development. Vaccines, like natural immune responses, need to elicit degenerate antibody production that is both specific and general. The immune system needs to perform two apparently opposite tasks: on one hand, it needs to recognize (to bind) with precision an infective external target or defective body cells while simultaneously avoiding other targets. On the other hand, it needs to recognize similar, but not identical, individuals of the same infective population (including future mutants). Thus, there is an evolutionary trade-off between specificity and universality in immune response.

Applied to vaccinology, degeneracy of T-cell receptors creates a complex phenomenon called "heterologous immunity" (Welsh and Selin, 2002), which explains how an immune response to a pathogen can provide immunity to a non-identical, related or even unrelated pathogen. Mounting evidence in humans shows that immunity to cowpox provides cover for smallpox (Stewart, 2006), the measles vaccine, given at an early age, provides protection against infections other than measles (Aaby et al., 2010), and the tuberculosis vaccine Calmette-Guérin (BCG) can provide some protection against leprosy (Setia et al., 2006) and mycobacterial infections (Mathurin et al., 2009). Vaccines can also have other beneficial non-specific immunological effects (Ritz et al., 2013). Similarly, veterinary virological vaccines are revealing unexpected infective protections, for instance, in pigs (Bragstad et al., 2013) and cats (Huang et al., 2010). The idea that vaccines protect only against a target disease has been replaced by a new paradigm where vaccines act on the immune system through spillover effects that influence subsequent exposure to unrelated stimuli—an example of pluripotentiality. Binding degeneracy in the immune system is possibly even related to the development of autoimmune syndromes (Selin et al., 2011) to which vaccines are showing a modulatory effect (e.g., Bourdette and Naismith, 2014). These findings are much in line with our definition of degeneracy stated above, as it is now recognized that multiple vaccines may have beneficial immunological effects for a given disease.

Finally, degeneracy seems to offer new translational tools for vaccine design, possibly with important implications for vaccine policy (Rothbard et al., 1989; Flanagan et al., 2013). For example, understanding the degenerate mechanisms of vaccine protection may not only reduce potentially untoward heterologous effects, but also allow to strengthen the coverage against certain diseases, like infections (Wilson et al., 2004) and cancer (Karyampudi et al., 2010), by timed, targeted and reduced vaccine administration.

Given the compelling evidence for degeneracy in immunology and vaccinology, pharmaceutical research would do well to incorporate principles of degeneracy in developing artificial, biology-inspired strategies in vaccine design. An extensive resemblance between pathogenic bacterial peptides and human peptides, i.e., molecular mimicry, governs many host-parasite immune interactions (Cohn, 2005), a framework where degeneracy can play both a theoretical and practical role. Degeneracy can be seen as a co-evolutionary constraint useful for conceptualising

common mechanisms of interaction between humans and infective parasites.

3. The brain: a most degenerate organ

Degeneracy is present across multiple scales of brain organization—from neurotransmitters and synapses, through cortical and subcortical regions, to the scale of multiple brains (Edelman and Gally, 2001; Noppeney et al., 2004). Degeneracy was introduced to neuroscience by Edelman as a key component of neural Darwinism, a selectionist account of brain development and function inspired by Edelman's work on degeneracy in the immune system. Neural Darwinism was formulated in part to explain the individuality and sheer variability of the brain across people (and animals), especially at the microstructural level (Edelman, 1987, 1988, 1992, 2004). This variability cannot be encoded in the genome as it exceeds by far the storage capacity of the human genome (Damasio, 2005). Analogous to the mechanism of cellular differentiation and selection of the immune system, neural Darwinism represents an account of brain organization whereby selective mechanisms are posited to operate over a population of neural connections (variants). These connections are retained or lost (selected) according to mutual affinity in their electrical activity. This process, akin to natural selection albeit operating at the somatic level, can be intrinsic or in response to experience. The population of structural elements (the connections) resulting from this selectional process will therefore be characterized by a non-trivial degree of variability. However, for the resulting brain networks to be functionally robust, structurally different elements must be able to provide similar outputs, that is, they must be degenerate. A degenerate network is thus able to provide reliable output even when the input is neither labeled nor identical across occurrences, and when the input is presented in a noisy environment with a large number of competing stimuli, which overwhelmingly characterizes the conditions under which the brain operates.

A second sense in which degenerate brain networks are functionally robust is in their resistance to damage. For example, even after losing 10% of brain tissue (Georgiou-Karistianis et al., 2013; Domínguez D. et al., 2013), people with Huntington's disease (HD) are still able to perform cognitive tasks at equivalent levels as healthy controls (Georgiou-Karistianis et al., 2014; Gray et al., 2013). Compensatory mechanisms may include increased activity in task-related brain areas that are primary targets of neuropathology in HD (e.g., the caudate nucleus and the dorsolateral prefrontal cortex during a working memory task) (Georgiou-Karistianis et al., 2014), or in brain areas that are both spared by the disease and not commonly recruited by the task (e.g., the inferior parietal lobe during an attention task) (Wolf et al., 2012). Both cases are examples of degenerate responses to tissue loss: in the first case, areas that have been changed structurally by neuropathology are still able to sustain regular output levels by increasing their response; in the second case, spatially segregated, functionally unrelated and structurally different areas, are recruited to take over or assist in supporting function.

A key corollary of degeneracy is that, because it entails diversity at the structural level, different circumstances may elicit different outputs from the same degenerate set. This one-to-many structure-function relationship has been dubbed pluripotentiality (Noppeney et al., 2004; Friston and Price, 2003). The pluripotentiality of a degenerate set distinguishes it from a redundant set, which comprises identical structures that perform the same unique function (see Fig. 2). Pluripotentiality is commonly observed in the brain. Recruitment of the default mode network in HD as mentioned above is one example, as activity in this network normally increases during internally driven cognitive activity but decreases during goal-directed tasks like the attention task used in the example.

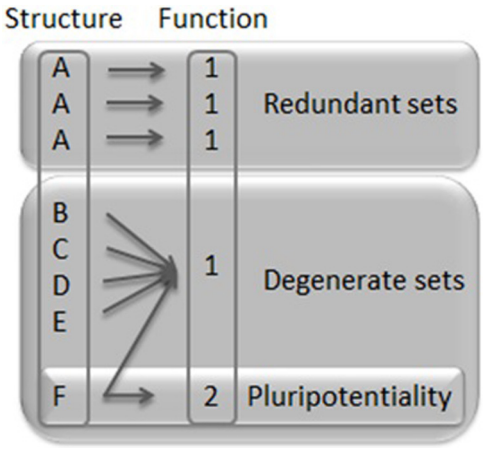

Fig. 2. Structure-function relationships in redundant (one-to-one) vs. degenerate (many-to-one) sets. Indicated is also the pluripotentiality (one-to-many) of a degenerate set.

While a dependency between degeneracy and complexity has not been formally derived, current work has shown complexity emerges wherever there is selection for high degeneracy (Edelman and Gally, 2001). This would suggest degeneracy is an essential ingredient of complex systems. The brain, dubbed as the most complex system in the universe, supports this proposition. Some scientists such as Ernst Mayr (1904–2005) found the choice of terminology puzzling (Mayr, 1994), but many neuroscientists have embraced the idea of degeneracy in the brain (Edelman and Tononi, 2000; Friston and Price, 2003; Price and Friston, 2002; Kelso, 2012; Leonardo, 2005; Levine, 2004; Noppeney et al., 2004; Park and Friston, 2013; Sporns, 2010; Sporns et al., 2000, 2005; Tononi et al., 1996; Tononi et al., 1999; Werner, 2007). According to one formulation (Tononi et al., 1999) complexity is high in systems where there is a high degree of both functional segregation and integration between constitutive elements with respect to a set of outputs. This functional independence and integration can only occur in a system with a high degree of degeneracy, such as the brain, where structurally different elements can contribute jointly to the same output but also independently to a different set of outputs (Tononi et al., 1999). Complexity, and by extension the brain, are therefore inextricably linked to both degeneracy and pluripotentiality. The brain is, in this sense, a most degenerate organ.

4. Beyond the biological sciences

An appreciation of the explanatory power of degeneracy is rapidly extending beyond the biological sciences. One area in which the concept is starting to be explored is linguistics, where degeneracy characterizes cases where multiple linguistic structures encode the same meaning (see Van de Velde, 2014; Winter, 2014).

As one particular example, consider the Korean language, which encodes politeness distinctions using honorific nouns, verbs, and grammatical markers (Sohn, 1999; Brown, 2011; Yeon and Brown, 2011). Politeness is simultaneously signaled via speech acoustics (Brown et al., 2014; Winter and Grawunder, 2012) and in fact, even just considering the acoustic dimension, there is degeneracy by virtue of a large set of acoustically diverse cues for politeness, including speech rate, pitch and loudness. In addition to these verbal and vocal cues, social distinctions such as levels of politeness are generally also signaled through bodily gestures

including bowing, a lower head position or adjustments to interpersonal distance (cf. Hall, 1966; Mehrabian, 1969). Hence, a single communicative intent—politeness—is characterized by many different communicative structures, ranging from low-level speech acoustics and body movements to high-level structures such as grammatical markers. Given the functional significance of politeness within Korean society, this comes as no surprise: having multiple degenerate cues is a more robust strategy of signaling politeness than relying on a single cue.

Language also exhibits pluripotentiality. Take, for example, pitch, which is a single acoustic dimension that expresses attitudes and emotions (Puts et al., 2006, 2007; Scherer, 2003; Tatham and Morton, 2004), grammatical differences (Gussenhoven, 2005; Ladd, 1996), information about specific consonants and vowels (Kohler, 1982; Ladd and Silverman, 1984; Ohala and Eukel, 1987; Ohde, 1984; Pardo and Fowler, 1997; Sapir, 1989) as well as information about the size, speed or position of the objects someone is talking about (Clark et al., 2013; Perlman, 2010; Perlman et al., 2014). Thus, the same acoustic material, pitch, encodes a whole suite of meaningful linguistic and non-linguistic distinctions. Considering pitch in relation to the above-mentioned example of politeness allows looking at linguistic degeneracy and pluripotentiality in tandem: Politeness is degenerately signaled by many cues, among them pitch, which itself participates in other aspects of the linguistic system, highlighting pluripotentiality.

Winter (2014) has outlined the implications of degeneracy for the study of linguistic systems with a particular focus on speech and sound change. Starting with the observation that speech is characterized by a large amount of acoustically diverse cues (see also Hawkins, 2010; Kingston and Diehl, 1994; Wright, 2004), Winter (2014) argued that such diversity is a precondition for linguistic change to happen. For one, linguistic degeneracy—as opposed to redundancy—means that structurally different cues encode the same meaning, which provides more variation that can serve as "fodder" for evolutionary change. On the other hand, degeneracy means that the speech system can evolve without becoming brittle—cues can change without affecting the total meaning because they are complemented by other cues, thus assuring robustness of the communicative system.

Degeneracy can be expressed across modalities in spoken and signed languages (Hodge and Johnston, 2014) as well as in music and dance (Mason, 2012). The concomitant use of deictic words and pointing gestures is a simple example. The Mickey Mouse relationships between sound and action in film (e.g., Mickey falls over to the accompaniment of a clash of the cymbals) is a more dramatic example. Multimodal degeneracy can be exhibited by a single individual who executes sound and movement at the same time, such as a dancer who creates self-accompanied sound (Kealiinohomoku, 1965; Mason, 2014a), or distributed throughout a group, such as an ensemble of musicians and dancers. Multimodal degeneracy may not always imply 1:1 relationships between sound and movement. In the Afro-Brazilian art of fight-dancing called capoeira, for example, rhythm, tempo and lyrics correspond to styles of bodily movement but not individual movements per se. Capoeira audience members can recognize stylistic elements of the performance either from listening to the music or watching the movement (Downey, 2002; Mason, 2013).

Applying the concept of degeneracy to the domain of humanly organized expression opens up new avenues for research, granted that researchers are able to find phenomenon-specific ways of operationalizing degeneracy. For example, we may ask the question whether cultural systems that have higher degrees of degeneracy are more prone to change due to the larger degree of substrate variability? And is it the case that more degenerate cultural systems are simultaneously more robust to perturbations of function? If highly degenerate cultural systems are more robust, does this lead to a higher transmissibility of those systems? And are communicative distinctions with high functional significance more likely to be degenerately encoded than communicative distinctions with less functional significance? Given adequate recognition of degeneracy in the domain of humanly organized expression, many of these questions can begin to be answered. Applications to speech have already been proven to be conceptually useful and to have potential empirical ramifications (Winter, 2014). Degeneracy, however, remains to be rigorously studied in other domains as well, such as gesture, music, dance and other cultural creations.

5. Concluding remarks

Many science terms have a different meaning in everyday language. Buffer, control, invalid, organic, primer, and sensitivity are just a few examples. Concentration, for instance, habitually refers to a person's attention but in chemistry it denotes the relative amount of a particular substance within a solution. As for degeneracy, the familiar usage of the word is completely at odds with its scientific meaning. In standard language, degeneracy denotes negative dilapidation, deviance and decay. In the natural sciences, degeneracy refers to the idea that different structural routes can lead to similar outputs. The scientific usage of the term "degeneracy" has a much less negative meaning than its popular usage. Nonetheless, the public understanding of degeneracy is so deeply engrained in popular culture that specialists have been slow to engage with its alternate meaning. This slow uptake has been bolstered by technological limitations, reductionist biases, and a political environment of research funding where complex biological models struggle to be rewarded. An aversion to a historically abhorrent term is understandable, but ignoring a key theoretical concept risks scientific models falling short. A traditional research approach of looking for a single cause for any given condition is not well suited to mapping how multiple processes yield a system's output. Overlooking degeneracy has implications for understanding and explaining living systems.

The analytical and explanatory value of degeneracy has been applied constructively in genetics, immunology and the brain sciences. As discussed, degeneracy obscures the causal links between structure and function, but living systems would have to be much larger without it. Many-to-one structure-function mapping, as revealed in the case of HD, illustrates the pragmatic importance of degeneracy. A central paradigm of neuropsychology rests upon the notion of necessary structures for a given function. A function can be declared necessary for a particular cognitive process if a selective cognitive deficit is produced by a focal brain lesion. If the brain has a degenerate architecture, however, as research indicates, then there may be no necessary regions. This has enormous practical implications—for example, the need to study patients with multiple lesions, as well as the need to analyze such patients using approaches that look at the interactions between different lesions.

The concept of degeneracy is finding application in linguistics as well as in other fields as varied as epigenetics (Maleszka et al., 2014; Lockett et al., 2014; Wojciechowski et al., 2014), sports science (Barris et al., 2013; Barris et al., 2014; Downey 2012; Komar et al., 2014; Schöner et al., 1990; Seifert et al., 2013, 2014), and evolutionary developmental biology (Specht and Howarth, 2014). Arrangements of a system are the result of complex interactions of multiple variables whose actions cannot be easily observed without changing more than one variable at a time. In dealing with complex systems, the concept of degeneracy is useful to think with and a valuable explanatory tool to communicate basic organizing principles. Making the history and theoretical breadth of degeneracy accessible allows its usefulness to be better

appreciated, its coherency to be further developed, and its application to be more quickly realized.

Words change meaning over time. For example, “standard” was once a word that referred to a banner raised on a pole carried by a flag bearer; “normal” comes from the name of a carpenter's tool to measure right angles; and “nice” used to mean stupid, ignorant and foolish. But what happens when the meaning of a word shifts and no term is left to take over the original meaning? If scientists refrain from using the word “degeneracy” because of its resemblance to “degeneration”, then we need a new term to refer to heteromorphic isofunctionality. Mason (2014b) has suggested introducing a hyphen to distinguish “degeneration,” as deleterious decay, from “de-generacy”, the structural diversity underlying functional plasticity. A different taxonomic solution, such as “divergence”, might prove more popular. Regardless of the terminological choice, it is necessary to clearly delineate degeneracy from redundancy and pluripotentiality, and to define one's terms accordingly. Precise nomenclature will help articulate the heterogeneous construction of the natural world. Degeneracy, the interchangeability of variable structures in achieving plastic outcomes, is a valuable concept that must take its place alongside variation, selection, memory, self-organisation, complexity and robustness in contemporary evolutionary theory.

Acknowledgements

With special thanks to Nicolai Parsons for comments and encouragement on an early draft as well as the reviewers whose feedback and suggestions inspired a significant shift in the scope of this review article.

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