How to find a scientific revolution: intellectual field formation and the analysis of terms

Bradly Alicea

Orthogonal Research Lab

bradly.alicea@outlook.com

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Abstract

Progress in scientific fields is usually thought to consist of formulating testable hypotheses and initiating paradigm shifts. Both of these views exclude the content of scientific fields that lead to milieu in which hypotheses and paradigms are formed. Therefore, it is proposed that a new view of scientific fields called coherence-based relevance be used to take into account the intellectual content of theories and how that can affect our view of both the history of science and the empirical world. The argument can be summarized by the argument that as scientific fields emerge, they are shaped by three forces: the historical contingency of the new field, the pattern of co-authorship and intellectual affinities within the field, and the salience of key references and citations within this social network. In this paper, the first two points will be tested with data (words from titles and abstracts) from selected journals and conference proceedings for four specific cases. When the same terms are used over time, it is indicative of stasis in terms of what is viewed as relevant in the field. A lack of similarity over time suggests a field in flux, at least in terms of relevant topics, theories, and methods. These results will be discussed, as well as the relationship between relevance, conceptual coherence, and changes in scientific practice over time.

Introduction

Imagine yourself at a conference a bit outside of your field. You attend the keynotes, parallel sessions, and poster sessions. All throughout the conference, you hear the utterance of key phrases, some used repeatedly throughout the conference, that resonate with the audience. Sometimes they are similar to their meaning in everyday language, but many act as jargon for a series of methods you do not fully understand. Although this seems to be a case of newcomer ignorance, there may also be a more systematic aspect to this experience.

We can take insights from relevance theory (Sperber and Wilson, 1995) to understand how scientific theories and fields develop. According to the relevance view, words and the terms they are embedded in have both an implicit meaning within a community and a relationship with the efficiencies of cognitive processing (Wilson and Sperber, 2004). The implicitness of certain words and phrases is useful within a community in terms of providing cues to context and intention. For example, the word “physical” may

have a more general meaning accessible to everyone in addition to an implicit meaning within a specific field. Such intention will be understood by an audience of specialists, and may automatically precipitate additional assumptions. The relevance of key terms is thus intersubjective, or understood through shared meaning.

Another reason why cognition matters to understanding communication in scientific fields is in terms of cognitive processing efficiency. According to this assumption, what is relevant directly corresponds to the amount of meaning the relevant term in question makes accessible to the scientist (Wilson and Sperber, 2012). This allows for more meaning to be transmitted per word or term, and attention to be allocated more efficiently. This is even truer of words and terms that are part of an established framework of ideas, as their intention is more powerful due to greater perceived reliability (Wilson, 2016).

According to this relevance-based view of scientific practice, some findings and topical themes not only become more relevant (and thus salient) than others, but also become prioritized in the form of key methods and unifying theoretical frameworks. Four examples (term-based similarity, term-based descriptions, and topical change/stability over time) from field-specific Conference or Journal Articles should provide a concrete example of how this works, and analyzing these terms in order of their prevalence across titles should yield the most relevant terms for that scientific field.

A relevance-based view of scientific practice includes contributions of *coherence*, *salience*, and *relevance*. Ultimately, coherence over time leads to theoretical synthesis, but is always constrained by relevance. In a very abstract sense, theoretical synthesis is a set of axiomatic statements derived from a finite set of terms that occur together at the same frequency. This can be distinguished from intellectual *coherence*, which occurs when sets of frequently used terms that retain their relevance over time. One example of this is the top 10 terms in a journal table of contents over the span of 10 years. Not only are these terms interrelated, but they also tend to persist together.

Methods

Formal Descriptions

In the process of acquiring a formal description, we seek to address the following question: in a given field, what is the proportion of new information that is discussed either through inclusion of new findings or revisitation of older topics? This will tend to be higher in cross-disciplinary fields, or fields derived from two or more antecedent fields. We will address several key terms in addition to introducing a heuristic logical model for the relevance-based evolution of practice in scientific fields.

This leads us to the question of how a collection of terms observed in modern scientific scholarship become specialized in different groups, and ultimately lead to the formation of new fields and subfields. We assume that very general terms form the most commonly used terms that are also shared within and between fields. Over time, fields become refined in their use of specialized terms, which often become restricted to specific research groups. However, these terms can occasionally diffuse between fields or subfields. Figure 1 summarizes this in the form of a binary semi-directed network, and shows the specialization of terms in black and the diffusion of terms in blue.

Figure 1. A hypothetical relationship (in the form of a binary tree) of how terms inform the structure of specific fields and subfields of study. The root node represents the most general term, while the leaves represent more specialized terms. Alternatively, this is a more general relationship of affinity or co-authorship (a) versus time (t).

The roots of these collective features have their roots in an attentional conception of scientific practice. The central argument is that ideas and concepts in a given field of study can be reduced to terms that have a *relevance* and *salience*, which are directly related to their syntactic and semantic content, respectively. Salience can be defined as all popular words of great semantic value in a table of contents (such as "group + selection", "evolution + development", "quantum + evolution", or "epigenetics"). Relevance can be defined as all technical terms in a table of contents (such as "phenotypic", "loci", "signal", "variation", "mutualism", "genetic"). Relevance increases when these words are used at a higher frequency, meaning that multiple authors or research groups are using the same terms. In this paper, we will rank all words/terms by frequency of occurrence, then remove words that have little to no potential semantic value (e.g. names of model organisms, conjunction words, and verbs).

Results

Example 1: Term-based similarity of Evolution and Evo-devo. To understand coherence as a tool for theoretical understanding, we can examine a controversy in the biology community over the so-called Extended Synthesis (Pigliucci and Muller, 2010). One issue revolves around whether the findings of the extended synthesis should constitute a paradigm shift, or whether the extended synthesis is best integrated into the predominant evolutionary framework called the neo-Synthesis (Laland et.al, 2014). We can explore this by surveying the titles of articles from a general journal in the field (*Evolution*) and a specialized journal (*Evo-Devo*), and then conducting three pairwise comparisons between the general journal, the specialized journal, and the general journal at an earlier time point. Similarities between lists for the top 50 most common words reveals a potential affinity between the two groups.

Figure 2. A three-way comparison for the top 50 most common words between *Evolution* journal in 1965, *Evolution* journal 2017, and *Evo-Devo* journal 2016-2017. Terms in common shown in parentheses along each arrow. All *Evolution* articles (1965 and 2017) were taken from the January, June, and December issues. For the *Evo-devo* dataset, all articles for the years 2016 and 2017 were used.

The three-way example in Figure 2 shows that there are an equal number of similarities between issues of *Evolution* journal from 1965 and current issues of *Evolution* and *Evo-Devo*. By contrast, there are 3x fewer similarities between *Evolution* journal in 1965 and *Evo-Devo* journal in 2016-2017. This suggests a compatibility between the *Evo-Devo* and modern evolutionary biology literature that rivals the stability of the *Evolution* literature during much of the time the Neo-synthesis has been a dominant theoretical framework. Given the dissimilarity between *Evolution* (1965) and *Evo-Devo* today, it seems plausible that papers published in *Evolution* have changed in a manner compatible with the *Evo-Devo* literature, but not turned away from the basic assumptions of the Neo-

synthesis. While the number of matches are equivalent, the terms have changed considerably as can be seen in Table 1 (Appendix).

Example 2: Term-based description of Biological and Cultural Evolution. To yield term-based descriptions of two conceptually similar and technically dissimilar fields (Biological Evolution and Cultural Evolution) published in a generalist journal (PLoS One), the titles and abstracts from seven articles were taken for each field and analyzed at the word level (see Table 2).

Table 2. Titles of articles and publication years for “biological evolution” and “cultural evolution” categories ($n=7$, $N=14$).

Biological Evolution	Cultural Evolution
Network Evolution of Body Plans (2008)	Cumulative Cultural Evolution and Demography (2012)
Origin and Evolution of Rickettsial Plasmids (2016)	The Pace of Cultural Evolution (2012)
Evolution and Diversity of SALMFamide Neuropeptides (2013)	Mapping the Evolution of Scientific Fields (2010)
Evolution of Oleosin in Land Plants (2014)	Anatomy of Scientific Evolution (2015)
Evolution of microRNA in Primates (2017)	Evolution of Conformity in Social Dilemmas (2015)
Intron Evolution: Testing Hypothesis of Intron Evolution Using the Phylogenetics of Tetraspanins (2009)	Modelling the Evolution of Social Structure (2016)
The Evolution of Enzyme Specificity in the Metabolic Replicator Model of Prebiotic Evolution (2011)	Evolution with Reinforcement Learning in Negotiation (2014)

The technical dissimilarity of each field is shown in the uniqueness of title words. Among all independent terms (subjects, verbs, and nouns) for each field’s sample, 21/23 terms in the biological sample were unique while 15/17 terms in the cultural sample were unique. This uniqueness is due to two distinct modes of scientific practice found amongst independent terms in the abstracts.

The first of these features has to do with the epistemological nature of field-specific practice. While we expect different methods to yield unique terms in each field, methods shared between fields might not consist of similar semantic tools within each field. While “network analysis” is referenced in both the biological and cultural sample, the term “network” is unique to the biological sample, while allied terms (“nodes”, “linked”, and “ties”) are unique to the cultural sample.

The second feature involves the existence of both unique and shared terms, the latter of which might point to a common ancestry of each field replete with shared methods and concepts. Terms unique to the biological ("lineage", "molecular", and "diversity") and cultural ("technology", "learning/algorithm", "conformity", "games/agents", "multi-level/cooperation") samples might represent technical and topical specializations within each corresponding field. Conversely, terms shared between fields ("species", "history", "model", "fitness", and "structure") represent some form of common ancestry or perhaps recent cross-pollination between fields.

Example 3: Change in NIPS topics over time. To understand how relevance and salience shift over time, selected paper titles from the NIPS (Neural Information Processing Systems) conference are used to examine whether the most frequently-used words changes over time. Six time points (1994, 2004, 2007, 2010, 2013, 2016) are used to assess the potential for these shifts and shown selectively in Figures 3 and 4.

Figure 3. NIPS Conference Accepted Papers for 10-year intervals. See Methods section for more information.

Figure 3 shows the change in top terms (relevance) across 10-year intervals. As expected for such a fast-moving field, the terms exhibit an almost complete turnover for each interval (4/15 terms are continuous between 1994 and 2007, and 5/15 terms are continuous between 2007 and 2016). The only three terms that are present in both 1994 and 2016 are "learning", "model", and "neural". These are consistent with the basic descriptive terms in our working hypothesis.

Figure 4. NIPS Conference Accepted Papers for 3-year intervals. See Methods section for more information.

Figure 4 demonstrates changes in top terms (relevance) between 2010 and 2016, using intervals of three years. As expected, there is more continuity between terms (8/15 terms are continuous between 2010 and 2013, and 11/15 terms are continuous between 2013 and 2016). The 2013-2016 interval is interesting in that two of the terms new to the 2016 list ("optimal" and "gradient") are descriptors of a word that was lost from the 2013

list ("algorithm"). This suggests that there was much coherence in research topics within this interval as compared the 2010-2013 intervals.

Example 4: Stability of GECCO topics over time. To provide a contrast to shifts in relevance and salience, selected paper titles from the GECCO (Genetic and Evolutionary Computation) conference are used to demonstrate stability in the most frequently used words over time. Three time points (2015, 2016, 2017) are used to establish the absence of shifts due to the short time intervals and the relative degree of stability in fields representing the conference programming. Selected results are shown in Figure 5.

Figure 5. GECCO Conference Accepted Papers for 1-year intervals. See Methods section for more information.

For both one-year intervals (see Figure 5), 11/15 terms are preserved from one interval to the next. The terms that exhibit this continuity are consistent with the idea of basic descriptive terms. This is sufficient as a signature of stability within communities, as it matches what is observed between 2013 and 2016 for the NIPS data. In the GECCO data,

we can also see the effects of short-term methodological trends in the data. The presence of Artificial Life (ALIFE) and Ant Colony Optimization – Swarm Intelligence (ACO-SI) in some years but not others might reflect cycles (or short-term waves) in the application domain's popularity.

Discussion

Relevance, Coherence, and Synthesis

The relative consistency of relevant terms over time can contribute to conceptual and even theoretical coherence. By contrast, changes in relevant terms might happen immediately before or after a paradigm shift. To understand why relevance leads to coherence, consider the assumptions we are making to come up with a measure of relevance. Recall that relevance is the frequency of terms in a list of titles. This means many authors or groups (often not in collaboration) are using the same terminology to describe the research they are presenting. Some of these terms merely describe commonalities of the field, but others describe methodological similarities across papers. When terms that persist in the top 15 terms for multiple years do so in a group, these terms are referred to as linked terms, and point towards coherent ideas in the literature. Linked terms appear in both the NIPS and GECCO data, but only seem to underscore the hypothesized root terms (see Figure 1) for each community. This is also true of the *Evolution/Evo-devo* dataset, although the use of common terms could be interpreted as common points of integration between the two fields.

Relevance as Presentation and Publication

One oft-overlooked aspect of determining scientific relevance is in how research and ideas are presented. While the traditional tools of PowerPoint presentation, journal publication, and conference publication are adequate for a summary of findings, these formats unwittingly serve as agents of bias. This bias stems from the structure of the PowerPoint program itself, which forces upon us a specific style of logical flow, and promotes vagueness in terms of both contextual detail and the difference between opinion and fact (Frommer, 2014). The PowerPoint example shows that structural frameworks, whether in the form of presentation styles that favor the salience of certain features or the linguistic description of concepts, can influence the procedural meaning (Wilson, 2016) of scientific practice.

Breakdowns in coherence as scientific revolutions

When new sets of findings or topical themes are adopted, the collective attention of a field is focused on a new set of features, and effectively puts the consensus view up for re-examination. The much celebrated idea of paradigm shifts (Kuhn, 1962) provides a template for this sort of change. Paradigm shifts are rapid changes in the prevailing

theoretical framework such that we should expect the coherence of many concepts to break down. This necessarily leads to rapid changes in the most relevant terms over short periods of time, perhaps on the time scale of 1 to 10 years. However, it must be stressed that the contextual value of these word lists are informative but not definitive. As such, persistent words and word matches are not always indicative of how the words are used. The most effective applications of this method are amongst closely related fields, or to the evolution of a single field over time.

Summary

Overall, this work provides an avenue to witness changes in conceptual coherence, and how intellectual synthesis emerges or dissolves. Imagine a directed network more fully interconnected than the case presented in Figure 1. In this context, the frequency of two terms co-occurring in a set of titles determines their connectivity in this graph, and provides a network topology that evolves as terms change in frequency. Because this network has a tree-like structure, pruning some nodes will have a greater effect on the network as a whole. In some cases, the decreased relevance of a single term can be enough to collapse the entire network, while in other cases all terms rise and fall in relevance with equivalent frequency.

Changes in either the boundaries of a discipline or increasing interdisciplinarity over time can also affect the connectivity of this network. According to Chen et.al (2015), one hallmark of interdisciplinary fields is the increasing scope of contributions from far-flung disciplines over time. In Figure 1, this would translate into a greater number of lateral connections, particular as the depth of the tree increases.

Finally, it is important to realize that these methods can be greatly refined, and may not prove predictive nor generalizable. The experience of Google Flu Trends over time demonstrates that simply using terms to predict specific events related to shifts in behavior is not particularly replicable (Lazer et.al, 2014). To achieve greater predictive power, words and search terms must be combined with richer forms of data and metadata to provide context. Titles and abstracts of published articles may simply not provide the contextual or descriptive richness of everyday scientific practice. Thus, these forms of data serve as an incomplete window into the process of consensus-building and influential discourse. Yet to acquire a broad map of the intellectual pathways that led us towards implicit meaning and consensus in scientific communities, the method introduced here is a first step.

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Appendix

Table 1. The top 50 most frequent terms in the title lists for *Evolution* (1965), *Evolution* (2017), and *Evo-Devo* (2016-7). All *Evolution* articles (1965 and 2017) were taken from the January, June, and December issues of their corresponding year. For the *Evo-devo* dataset, all articles for the years 2016 and 2017 were used.

<i>Evolution</i> (1965)	<i>Evolution</i> (2017)	<i>Evo-Devo</i> (2016-7)
species	selection	expression
population	evolution	gene
natural	genetic	development
evolution	divergence	developmental
isolation	diversification	genes
populations	environments	conserved
characters	life	differences
hybridization	size	evolution
hybrids	traits	evolutionary
sexual	effects	formation
size	gene	genetic
structure	reproductive	head
sympatric	sexual	molecular
tetraploid	adaptation	patterning
allopatric	adaptive	phenotypic
chromosomal	choice	plasticity
chromosome	diversity	system
complex	evolutionary	analysis
different	isolation	ancient
estimation	male	aphid
evidence	mechanisms	body
fertility	phenotypic	changes
frequencies	affect	comparative
gene	aging	control
genetics	allometry	domain
hybrid	barriers	early
island	birds	establishment
mating	color	growth
method	competition	heterochronic
populations.	consequences	homologs
quantitative	ecological	hox
races	expression	insights

related	genomic	integration
selection	habitat	meeting
(co)variation	history	novel
adapt(ive/ation)	introgression	patterns
behavior(al)	maintenance	pea
allocation	mate	regeneration
analysis	maternal	sex
ancestry	mitonuclear	acid
background	multilevel	acquisition
bioclimatic	natural	adaptation
biology	parallel	amino
branching	patterns	analyses
classification	plasticity	aortic
colony	ploidy	apetaly
comparing	polymorphism	appendage
competition	population	arch
congeneric	prey	axon
derivatives	quantitative	bacteriome