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Towards an evolutionary model of science dynamics: generation and production of scientific knowledge

Abstract. The paper proposes a modified version of BVSR model of research process. At the level of individual heuristics-driven variation it uses beta (IBP) and Dirichlet (CRP) random clustering processes. At the SR level it elaborates two main research strategies based on team reasoning principles: inventive and explorative strategies. They are differentiated by the phase of "heuristics routinizer".

Key words: research process, heuristics, scientific routine

Ku ewolucyjnemu modelowi dynamiki nauki: generowanie i produkcja wiedzy naukowej

Abstrakt. Artykuł wprowadza model procesu badawczego jako modyfikację BVSR. na poziomie zmienności jednostkowej proponuje process beta (IBP) oraz Dirichlet (CRP) jako losowe procesy klastrowania. Na poziomie SR opracowuje dwie zasadnicze strategie badawcze, oparte na zasadach myślenia zbiorowego: strategie przełomową oraz odkrywczą. Są one różnicowane przez fazę określaną jako „rutynizacja heurystyki".

Słowa kluczowe: proces badań, heurystyka, rutyna naukowa

1. Introduction

The process of creation of scientific knowledge throughout the research process has been a topic of occasional rather than systematic studies in philosophy of science. For instance (Nickles 2009, 2016) offers BVSR (blind variation selective retention) model as an alternative to the traditional accounts of research process. (Hessels et al. 2011) adopt a modified version of B. Latour's and S. Woolgar's model of research cycle. (Carrier 2011, Koepsell 2015, Mirowski 2011, Radder 2010, Scharnhorst et al. 2012, Zamora-Bonilla 2016) make occasional comments regarding commodification of the early stages of research process. This lack of interest contrasts with the major shift in more recent accounts of production of

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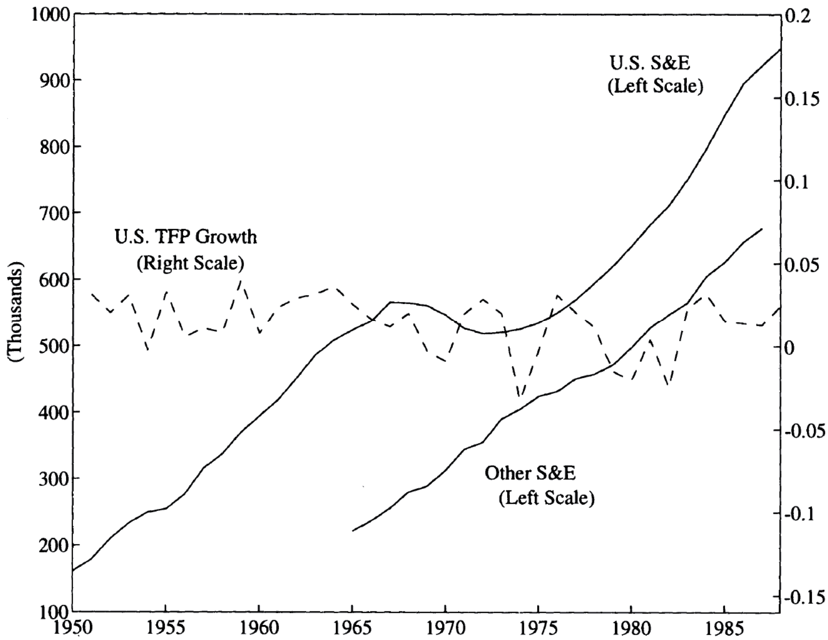
scientific knowledge (Gibbons et al. 1994, Nowotny et al. 2001) and the commonly adopted in philosophy of science perspective on "science as a process" (Collins and Evans 2009, Collins and Evans 2002, Devlin and Bokulich 2015, Fuller 2007, Hacking 1999, Hull 1988, Kitcher 2001).

While the voluminous economic literature focuses on "scientific knowledge production", it contributes little to our understanding of the mechanism of its creation. Rather, it undertakes an epistemically generic characterization of contribution of the production of knowledge to economic growth (elaborating on the original contributions of P. Samuelson and V. Bush as well as economists affiliated at NBER in 1950's). Within the three major strands of the explanations within the endogeneous model (Antonelli 2017): scale effects (e.g. Romer, Grossman, Helpman, Barro), per capita income (e.g. Jones, Kortum, Segerstrom) and two channels (e.g. Aghion, Howitt, Peretto, Young), none engages the epistemic perspective.

Figure 1. Misalignment between FTE as a proxy measure of knowledge capacity and economic growth (TFP)



Source: (Jones 1995, p. 763).

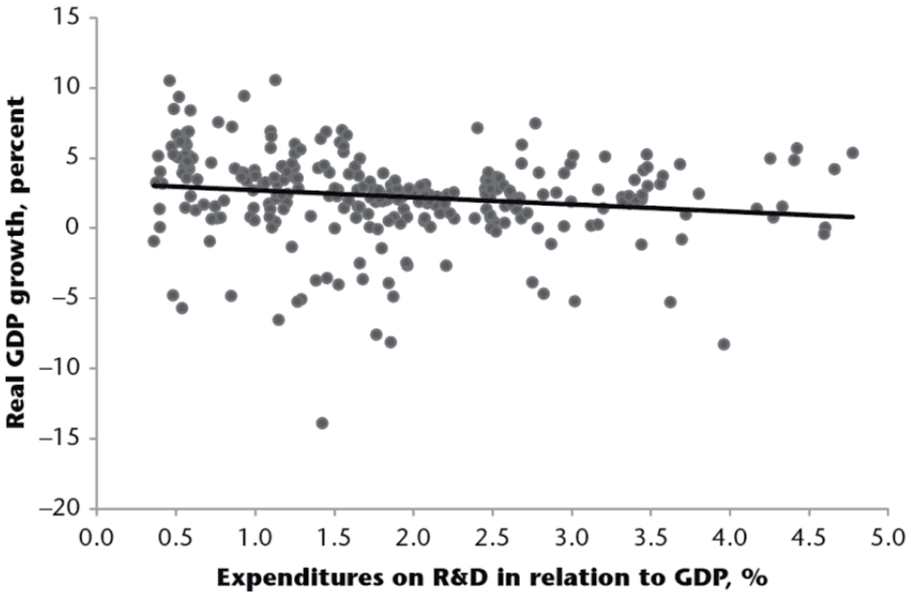
Another relevant literatures concern generation of scientific knowledge in the social context. Out of the eight major proposals: Mode 2 knowledge production (Gibbons, Nowotny et al.), finalisation science (Böhme et al.), strategic research/

strategic science (Irvine, Martin), post-normal science (Funtowicz, Ravetz), innovation systems (Edquist et al.), academic capitalism (Slaughter, Leslie), post-academic science (Ziman) and the triple helix (Etzkowitz, Leydesdorff), only the second explicitly accounts for the epistemic aspect of science generation (Böhme et al. 1983). Nonetheless "we still do not fully understand why technological abilities show, for mature economies in steady state, a constant annual growth rate of between one and two percent" (Gries 2017, 20).

The above mentioned literatures are replete with paradoxical observations concerning the concept of knowledge. In particular, there are many counterexamples to the standard proxy measures for knowledge stock. For instance, the R&D employment level (FTE) – as observed in (Jones 1995, p. 763) – does not correspond to total factor productivity as depicted in the figure, while on the standard assumption it is a proxy measure of knowledge production capacity in a given nation. And – since knowledge is the main factor of economic growth, besides the traditional ones of capital and labor – it would be expected to correlate with TFP.

Another, perhaps the most prevalent, measure of knowledge production is R&D expenditure. Again, there is evidence of poor correlation, if any, between the level of R&D and economic growth as measured by GDP (Braunerhjelm 2012 p. 290). It is depicted on figure 2.

Figure 2. Poor correlation between the level of R&D and economic growth as of GDP

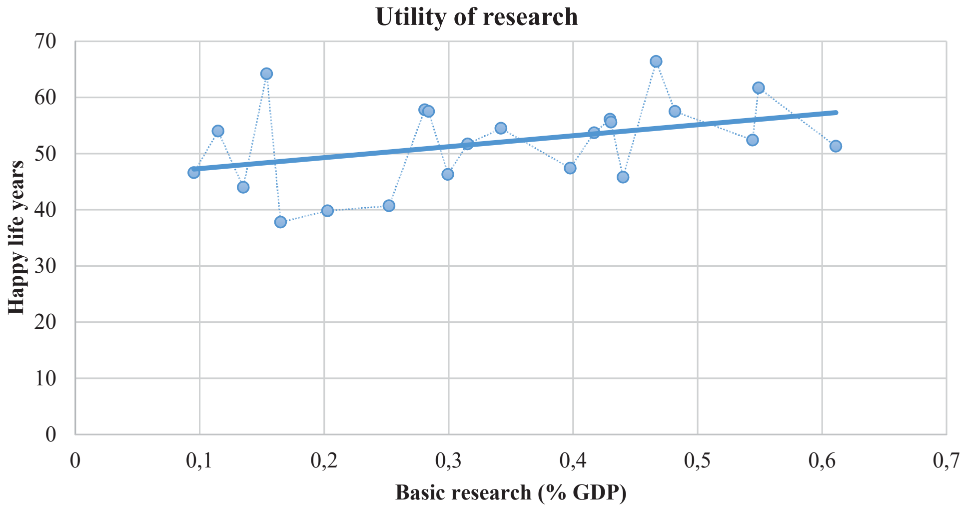


Source: (Braunerhjelm 2012, p. 290). The data are for 33 OECD countries for 2001–2009.

Even data on patents are found problematic. In the study of CIS data (Brouwer and Kleinknecht 1999, p. table 1) on the effectiveness of innovations at firm level patents are found to three other mechanism of protection against imitators.

I provide yet another aggregate perspective to indicate that the standard economically oriented approaches do not adequately capture the concept of knowledge and its broad social role. Figure captures the broad utility of knowledge as a contributor to social wellbeing by a standard measure of happy life years against the level of expenditure on basic research as a proxy measure of the most creative knowledge stock. The indicated trend line does not apparently explain such outliers as Mexico or Czech Republic.

Figure 3. Problematic contribution of knowledge to social wellbeing



Source: OECD statistics and HLY database (https://www.purposeplus.com). Data for 2014 for countries covered by both sets of data.

These perplexities and discrepancies motivate a more systematic epistemological account of knowledge and its generation. The presentation of my HDVSR model, elaborated below, is preceded by a discussion of *situated epistemology* – the general epistemological standpoint adopted here.

2. Situated epistemology

Scientific knowledge is the general factive mental state. With knowledge it shares the characterization as broad and prime condition. I take for granted T. Williamson's delineation between the internal and external condition: "The internal will be identified with the total internal physical state of the agent at the relevant time, the external with the total physical state of the external environment" (2002, 51). So, knowledge as an integral combination of both kinds of conditions is prime, while belief – including true and justified belief – supervenes on the internal condition. The gist of the argument follows.

As in the general case, scientific knowledge is a prime condition. It is not a composite of the internal and external conditions. The argument is analogous to the general case. As demonstrated by Williamson (2002, 67–68) a condition C is prime iff there are three different conditions α, β and γ such that γ is internally like α, and externally like β and while C holds in α and β, it fails in γ. Suppose now there are two different ways for C to obtain. Let DM1 be a data model for a given phenomenon, like a disease, and TM1 a corresponding theoretical model, which, suppose causally explains the phenomenon, and which is nurtured by a given scientific community S. Suppose that in α TM1 fits DM1 (external condition), and the community S nurtures TM1, while an alternative model TM2 does not fit DM2 and S rejects to nurture TM2. In β, conversely, TM2 fits DM2 and S nurtures TM2, while TM1 fails to fit DM1, and S does not nurture TM1. Hence, S knows the cause of the disease in α and β. In the case γ, which is internally like α, and externally like β, S fails to know the relevant cause as it nurtures TM1, which fails to fit DM1, and it rejects TM2, which fits DM2.[1] The genuine research endeavors, which aim at creation of scientific knowledge I will refer to as *knowledge generation*. In contrast, the attempts in science to expand beliefs supervenient on the internal condition I will call *knowledge production*[2].

The extensional equivalence of evidence and knowledge $E = K$ is also taken for granted here. I am not going to repeat the whole argument supporting this claim, but let me only focus on its part, demonstrating that justified belief is short of evidence. Suppose that a series of $n + 1$ draws of balls with return from an urn was filmed. All ball were red. I watch the drawing of the first n balls. Thus I know that n balls were red and my knowledge is the evidence on which I make the expectation that the next one will also be red. Consider two hypothesis: H_1: n balls are red and $n + 1$ ball will be black; H_2: ball 1 was black and balls 2, …, $n + 1$ are red. The proposition that ball 1 was black is false and is inconsistent with my evidence. The proposition that ball $n + 1$ is black is also false, but is consistent with my evidence concerning the first n balls. Consider now the proposition that the $n + 1$ ball is red. Given my evidence, this proposition is justified and is consistent with it. However, since the proposition that the $n + 1$ ball is black is consistent with my evidence (in

[1] A notable historical illustration of the case γ is the 19th debate in the UK on the causes of cholera outbreaks. The Committee of Scientific Inquiries, constituting part of the parliamentary commission the Board of Health, nurtured the miasma theory, which did not fit its data model, while John Snow elaborated an alternative model of cholera as contagious disease, which was rejected by CSI.

[2] Here, I will not go into the details, but only mention that the most eminent form of knowledge production seems the activities undertaken by contract research organizations as described in detail by (Mirowski 2011).

contrast with the proposition ball 1 is black), then obviously the proposition $n + 1$ ball is red is not part of my evidence, even though it is justified and true.

In analogy with the distinction between action vs desire and knowledge vs belief I propose yet another: *expectation* vs *speculation*. Speculation supervenes on the internal condition as it projects beliefs unto the future. It is sometimes identified as "wishful" thinking. In the case of scientific knowledge in general the projection of the internal condition is in general tantamount to deriving consequences of a symbolic representation (see for a detailed argument see section 3) and projecting them onto the unknown territory. As the link with the external condition is not preserved, the projection could not turn into knowledge and there will be mismatch between the projection and new evidence. This, however, can be overcome by the well-known maneuver to supplement with some *ad hoc* hypotheses. This, eventually will lead to either an internal inconsistency or the inconsistency with the upcoming evidence (a detailed exemplification is presented in section 3).

The prevalence of the internalist account of knowledge creation is most likely due to origins of an account of scientific research process by Descartes. In sketching the path leading to his own discovery of 'scientific method' he admits:

> […] as soon as I reached an age that allowed me to escape from the control of my teachers, I abandoned altogether the study of letters. And having decided to pursue only that knowledge which I might find in myself or in the great book of the world, I spent the rest of my youth travelling, visiting courts and armies, mixing with people of different character and rank, accumulating different experiences, putting myself to the test in situations in which I found myself by chance, and at all times giving due reflection to things as they presented themselves to me so as to derive some benefit from them. (Descartes 2006, p. 10)

Instead, Descartes decided to pursue his own 'method of research' by transgressing scientific routines altogether: "[…] learned not to believe too firmly in anything that only example and custom had persuaded me of" (Descartes 2006, p. 11). And this cleared the path for his own method:

> […] I took the decision one day to look into myself and to use all my mental powers to choose the paths I should follow. In this it seems to me that I have had much more success than if I had never left either my country or my books. (Descartes 2006, p. 10)

This may well be how the internalist account of scientific research originated. The famous textbook (Arnauld and Nicole 1996) standardized this account of scientific research, at least in philosophical literature. On this account science (internally) generates hypotheses, which are then empirically tested and – positively or negatively – confirmed. Popper's novelty with regard to this logical empiricist standard may be seen as an attempt to undermine the internalist account of research process. I see Popper's call for bald conjectures as a far cry for the idea of research as an unfolding process, which is not accomplished by a conjunction of internal and external conditions. Unfortunately, Popper framed his own account following the internalist pattern of the logical empiricist conception.

Expectation, in contrast to speculation, identifies a new relation between the elements of knowledge, which itself is not part of the body of knowledge (for a detailed argument and presentation see section 3). The *knowledge creation process* consists in transforming the body knowledge to accommodate the new relation or its logical transformation. In the case of scientific knowledge the process is driven by a heuristics, which determines the level of novelty.

3. HDVSR Model of Research Process

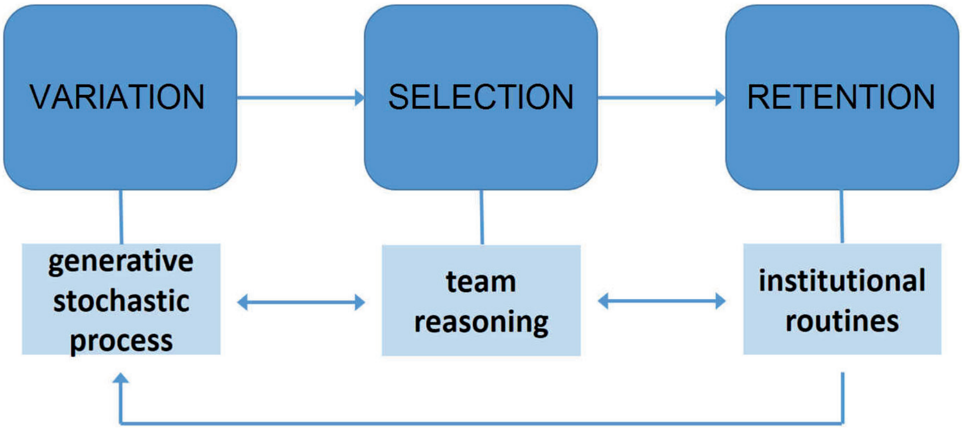
Traditional accounts of research process, stemming from the early works of F. Bacon and Descartes, have focused on two strategies based on inductive vs. deductive inference (Ladyman 2007, Losee 1993). On the inductivist account data acquisition is a constitutive element of research process and creation of scientific knowledge. The empirical data are interpreted and generalized to serve explanatory role and systematically accumulate to form theories. Deductivism, in contrast, rejects inductive inferences as logically invalid, and therefore focuses on how the consequences of 'bold conjectures' confront the empirical evidence. These two strategies are criticized by proponents of evolutionary epistemology (Nickles 2009) as uncapable of accounting for the sources of new knowledge in science. This limitation, as claimed by T. Nickles, is supposedly overcome by an approach constituted by two components of scientific method: blind variation (BV) and selective retention (SR): "Novel design evolves – *emerges* – from a multi-stage process of cumulative adaptation" (2009, p. 186).

In the original formulation the variations are generated "blindly":

> To include this process in the general plan of blind-variation-and-selective-retention, it must be emphasized that insofar as thought achieves innovation, the internal emitting of thought trials one by one is blind, lacking prescience or foresight. The process as a whole of course provides "foresight" for the overt level of behavior, once the process has blindly stumbled into a thought trial that "fits" the selection criterion, accompanied by the "something clicked," "Eureka," or "aha-erlebnis" that usually marks the successful termination of the process. (Campbell 1960, p. 383)

As presented below, the BV component is elaborated by D. Simonton in his model of creativity vs sightedness. In more general terms the creation of scientific knowledge is driven by some kind of heuristics. It might be – as proposed by the proponents of the BVSR model – a mere trial-and-error method, but some more sophisticated heuristics might also be used (Gigerenzer and Brighton 2009). To reflect the role of heuristics I propose to use the acronym "HDVSR" to reflect the heuristics-driven variation of scientific knowledge. The outline of the HDVSR model is presented in figure 4.

Figure 4. HDV SR model of ontology and dynamics of scientific research process



Below I propose to identify four kinds of heuristics in creation of scientific knowledge. Two that are related to generation of genuinely new knowledge are: *inventive* strategy oriented towards a discovery, which leads to a substantial revision of the initial conceptual framework, and *exploratory* strategy to generate new knowledge by forming new relational dependencies within the initial conceptual framework. *Application* of scientific knowledge to a new domain of objects constitutes the third strategy, while a creation of new conceptual frameworks without advancing knowledge is recognized here as a spurious strategy[3].

Admittedly, the BVSR approach is limited as it is based on highly contextualized and domain-specific knowledge (as the basis for BV), while also less efficient than fully controlled problem-solving strategies. (Simonton 2015) takes 'blindness' as the extreme pole of the continuum leading up to 'sightedness'. The latter is defined as $s_i = p_i u_i v_i$, where p is the probability of a given combination of ideas i in set X and represents inverse of its originality $(1 – p)$, u – its utility (most often binary 0 or 1), and v – creator's prior knowledge of the utility, which is the inverse of its surprisingness $(1 – v)$.[4] Thus, blindness is the opposite: $b_i = 1 – s_i$. For the whole set X of k combinations sightedness becomes: $S = 1/k \sum p_i u_i v_i$, and blindness $B = 1 – S$. The tradeoff is presented in figure 5.

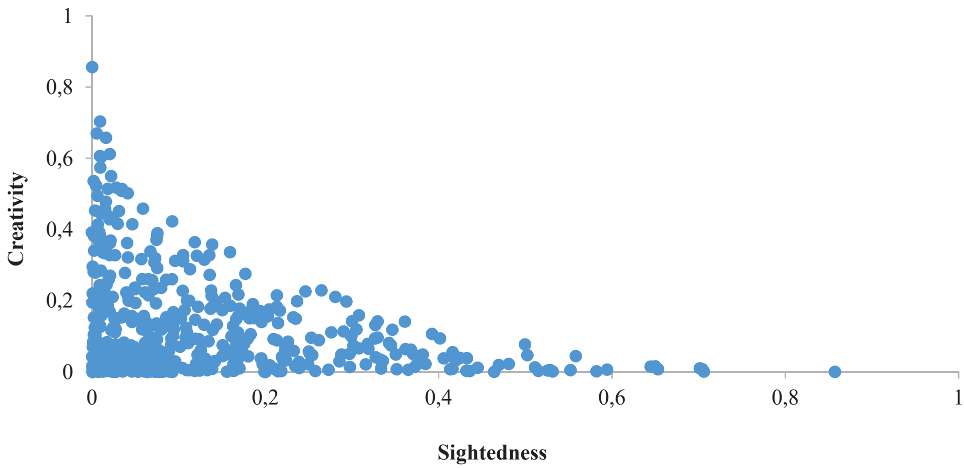
Sightedness is related inversely to creativity, which is defined as the product of originality (the inverse of probability), utility and surprisingness (the inverse of prior knowledge), i.e. if s_i and S increase, creativity c_i and C accordingly decreases. Simonton (2015, 264) explains: "That decline occurs because the set then converges on routine or reproductive combinations representing domain-specific expertise,

[3] I am not going into the details here, but it appears likely that the rationale for the spurious research is some kind of marketing effect, for evidence see e.g. (Applbaum 2006, 2009).

[4] This corresponds to the nonobviousness criterion used by the US Patent Office and is decided by an expert with 'ordinary skill in art' (Simonton 2015, 264).

ultimately yielding $k = 1$ (i.e., the undeniably and already known single best combination)". Figure 5 depicts the fact that most creative ideas are located at the blindness end of the spectrum. This, in turn, justifies BVSR as the variance of creativity is greatest at the maximum level of blindness. In other words, the most useful creative ideas are generated among the whole variety of useless ones. Simonton takes this to be the risk of the creator, but also her ingenuity in sorting out the valuable ideas among the plenty useless ones. Two historical case study amply illustrate how useless and false ideas outnumbered the most creative ones in the case of Galileo and T. Eddison (Simonton 2012a, 2012b, 2013).

Figure 5. The relation between sightedness and creativity



Source: plotted with random number generator on the basis of (Simonton 2012).

Further, Simonton distinguishes various forms of BVSR. It could be either external or internal, depending on whether its utility is tested against the external world (e.g. in laboratory experiment) or against a mental representation (e.g. Einstein's thought experiments). BVSR can proceed in a sequential or simultaneous manner, depending on how the ideas are tested, for instance a typical example of simultaneous BVSR is clinical trial with the treatment and control groups run in parallel, while internal testing of ideas in accordance with their initial probability is an instance of sequential BVSR.

Next, BVSR may be used in exploration or elimination, depending on whether the set X is recognized to contain at least one element with nonzero utility. Typical cases of discovery illustrate futile exploratory attempts, like Edison's failed attempts to produce organically based tires. While some examples, like J. Watson's discovery of the DNA base code (Simonton 2015, 264), well illustrate the elimination BVSR.

Finally, different kinds of BVSR depend on preselection process, which precedes the application of BVSR. Simonton characterizes the preselection process rather broadly, to embrace not only scientific research, but also artistic creativity, and concludes thus: "In short, preselection means that BVSR starts under the assumption that certain combinations will never pass the utility criteria" (2015, 265). But the conclusion seems to undermine the earlier explanation, where he admits, for instance, that preselection in physics means that no one will propose a combination of ideas, which contradicts the fundamental laws of physics. This observation opens a more fundamental question, namely what would make BVSR adequate with regard to knowledge creation in research process?

As it stands, BVSR on Simonton's generic account is claimed to be widely applicable to any kind of creative process, including research. Two topics seem pertinent.[5] The preselection process, including the specification of the combinatiorial 'alphabet', and utility are – independently of one another, as I claim – the possible sources for characterization of BVSR that fits research rather than any other kinds of activities. Let us focus on the preselection process first. The recent re-evaluation of T. Kuhn's – perhaps too radical – discernement between normal and revolutionary science clearly exemplifies the claim that a precondition for a scientific problem is that it based on previous research (Devlin and Bokulich 2015). Thus, in the case of preselection process in scientific research, it is required that it be motivated by previous research. Even the apparently most disrupt or transformative kinds of research must satisfy this condition. It not only directs preselection, but also largely determines the relevant 'alphabet' of ideational combinations.

Given Simonton's comment above, however, it is apparent that an argument is needed to demonstrate that preselection is an independent characterization of BVSR than utility. The latter is taken as a binary concept, because on Simonton's account the inventor evaluates the usefulness of a given combinatorial idea and decides either to pursue it, or modify.[6] It seems, however, that the evaluation is accomplished in terms of the background knowledge and upheld scientific beliefs. Analyzing the case of Gallileo, Simonton claims that the role of background knowledge may be non-trivial, because it may expand inventor's understanding of data beyond the routine way. However, even in this case the new ideational combination is based on the same set of elements as the preselection process.

[5] I do not enter here a systematic discussion to what extent Simonton's BVSR definitions constitute an adequate articulation of BVSR nature of creative process in science. It could only be remarked, though, that the definitions are static in the sense that they do not capture how new generations of ideational combinations stem from the previous ones. Nickles (2009), for one, claims that this dynamics is well captured by J. Koza's genetic programming.

[6] Apparently, utility is taken here in its epistemic meaning. Given the commercialization of research tools (Mirowski 2011) it seem problematic to ignore the non-epistemic utilities of scientific ideas even at the initial stage of basic research, not to mention applied research or the subsequent stages of development and market diffusion.

Hence, preselection and utility seem to be driven by the same or very similar concerns.

My argument rather would be that preselection and utility apply to different kinds of units. Thus, preselection in scientific research operates on a symbolic representation, which is adopted in a communal practice. Note first that – given the historical studies on science – it is only since the 19th century that scientific research in the modern sense is applicable. This may be amply illustrated in the transformation of engineering sciences, which up to the early 20th century were almost without exception based on trial-and-error recombinations of the antecedent failed attempts by the inventor. The detailed account of the emergence of General Electric Central Research Laboratory or the research at AT&T pins down the stages in the successive transformation of the trial-and-error approach into an approach based on scientific symbolic representation, driven by scientific theories.

The preselection process, apparently, is bound not only by the *content* of the pertinent symbolic representation, but also by its *institutional setup*. The latter is not limited to formalized scientific institutions, but includes also the standard scientific practices derived from a given symbolic representation. Perhaps the first modern institutional setup of this kind is instantiated by Tycho Brahe's *Uraniborg* as a complex network of scientific instruments, observational practices using them, but also specially designed buildings and even the economic order as an enforced effort to provide economic means for the research activity. The composition and structure of the elements of *Uraniborg* were driven by the symbolic representation, namely the geo-heliocentrical model, whose confirmation vs the alternative heliocentrical model required the then most precise observations of Mercury. The numerous visitors of Hven, where *Uraniborg* was installed, diffused the newly emerged practice of combining mathematical description with the use of the most precise observational instruments, while founding the most important observatories throughout Europe. *Uraniborg* was presumably first to institutionalize modern research practice integrated with a particular symbolic representation. Hence, when Kepler overtook Brahe's secret notebooks with the data on Mars, his ideational preselection was based not just on the *content* of the notebooks, but also by the institutionalized practice of precise mathematical observations initiated on Hven.

The communally institutionalized practice based on a shared symbolic representation I call *scientific routine*. My claim, as illustrated by the initial historical case of *Uraniborg*, thus is that it is scientific routines that constitute the framework for preselection in the BVSR process. In particular, as is presented in more detail in below, the preselection process is based on heuristics routinizer, which determines the conceptual framework used to develop a heuristic strategy which determines the research process. It is only against the heuristics that the utility evaluation of a given ideational recombination takes place. If successful, it is subsequently retained as a basis of a new scientific routine. I pursue here the HDVSR model of scientific routine evolution, because it apparently fits the historical record more adequately than alternative accounts, especially the view of revolutionary changes.

However, the original BVSR model misses out one critical component, which is rather evident in those historical cases. Namely the *nurturing* of ideas. If it is admitted that an ideational recombination is conditioned by scientific routine, then this recombination can only be claimed as retained if it gives rise to a new scientific institution. Consider, for example, the discovery of cholera back in the 19th century. To meet the acute challenge of unexpected outbreaks and numerous victims the British Parliament set up Board of Health, including Committee for Scientific Inquiries (CSI). The latter, led by notable researcher William Farr, followed the then routine miasma theory. John Snow, a physician who early in his career treated cholera patients, came up with an alternative idea of cholera as contagious disease caused by an unobserved parasitic organism, which gets into a digestive system of a victim by a direct contact or water. To substantiate his hypothesis Snow collected a lot of evidence, e.g. the natural experiment in the Southern London, where he established that the incidence of the disease among using contaminated water was nine times higher, the famous removal of the water pipe handle at the Broad street pump, which stopped local cholera incidences or his detailed explanations of every case of cholera incidence. The report summarizing the evidence was nonetheless incorporated into the dominant miasma theory as indicating that water is a ‘contributing’ – rather than as claimed by Snow the main cause of the disease. Some fifteen years later it turned out that Snow was right, but he failed to institutionalize a new research practice based on his symbolic representation and therefore he failed to give rise to a new scientific routine. It was only possible after Koch’s research, which used his new experimental routine for the demonstration.

Snow’s case is a good illustration that retention of a given idea is a complex phenomenon, which is surely not limited to the contents of the new recombinational idea alone, but hangs also on the accompanying emergent practice. It is this practice, as I argue, that *nurtures* the idea and is a necessary condition for its retention by a scientific community. Once the practice becomes institutionalized and adopted by scientific community, a new scientific routine has emerged, which, in turn, conditions the preselection process for the successive applications of BVSR process.

The variation process in the HDVSR model does not, of course, use Simonton’s original combinatorial process as it simply supervenes on the internal states. In contrast, as indicated in section 2, expectations do not supervene on internal states of the subject. Let us consider it in more detail with the following exemplification. Suppose there is a group of people $A = \{a_1, \ldots, a_n\}$. Each person enters the same restaurant for lunch. The restaurant is so organized that it has as many kinds of lunch sets as there are tables and that a given lunch set L_i is served at the table i.

So, if a given person joints the table i, she will be served the lunch set L_i. Assume also that each person gets only one lunch set, while any number of persons can join a given table. Our evidence includes knowledge about shared features of the persons in the group $F(.)$ and we also know how many of each lunch sets $L_1, \ldots, L_i$ have been served. Our mathematical knowledge tells us that the number of lunch sets served depends on the order of tables chosen by the group members. We don't know, however, how these lunch sets were distributed among the particular individuals from the group. Our expectation is that there is some dependence between F and G meaning the distribution of lunch sets among the individuals: for $a_1, \ldots, a_n$ it holds that $F(x) \rightarrow G(x)$.

Now, in order to empirically ground this expectation, we need to transform our knowledge – both in its theoretical and empirical dimensions (van Fraassen 2014; Kawalec 2017). Firstly, it is necessary to theoretically characterize the relation between the elements of the group in a way which would allow a unique measurement of the assignment between a given person and her chosen lunch set L. Secondly, the measurement procedures have to be elaborated to capture the assignment. As a consequence of these twofold transformations of the previously held knowledge we obtain a new knowledge on the process and the properties of each group member and her chosen lunch set.

Let us consider this case in more detail. Suppose, we have a data series: {hc, gc, hc, ?s, gc, hc, ?s, ?s, hc, ??}. We use a conceptual frame F, which contains just two categories, namely color C = {hazel, green} and shape S = {circle, square}. So, the expectation we form concerns a relation R between the color of an observed object and its corresponding shape: R(C, S). The relation R is not part of our knowledge, but the colors and shapes in F are known. Also the points in the data series we observed are part of our evidence e. However, our evidence is not sufficient to recognize all data points nor to define the relation R of interest. In order to proceed with the latter task we need, as argued earlier, the twofold transformation of our original projection in order to ground it empirically. So, first, we elaborate some theoretical relationships between the variables, and next, we enhance our measurement capacity to capture the value of the variables. Suppose that in our case it is accomplished by: 1) an analysis of the compound colors, the identification of the primitive colors and elaboration of theory of color mixing; 2) the generalization of the notion of square and forming the notion of regular polygon. Corresponding to that we now expand the scope of the two categories to obtain: C* = {hazel, marine, yellow, blue, red} and S* = {circle, square, pentagon}. Once we have the ability to measure them, we can reconstruct all the points in the data series: {hc, gc, hc, bs, gc, hc, ys, bs, hc, rp}. The expanded categories of color and shape as well as the observed series are now part of our evidence e^*. This allows us to determine the relation R, holding between C* and S*, which also becomes part of e^*. Now, we are in a position to *explain* the relation between C* and S*, by claiming that the colors {b, y, r} occur with polygons, while the mixed colors – with circle shape. What follows next, is *generalization* of the original projection to form a general probabilistic regularity holding between all the elements of the investigated class of objects: $\forall_{a \in A} R(C, S)$. What leads me to form this general claim is the observation that there is a random clustering process underlying the distribution of colors among different shapes of objects known as the Chinese restaurant process (CRP in short). Corresponding to tables in CRP and the lunch sets served we have a fixed combination of color and shape, for instance – hc first, then – gc, third – bs, fourth – ys, fifth – rp, etc. Now, I am able to make predictions concerning the forthcoming data series and this general relation becomes a new element of my evidence e^{**}.

In contrast, consider now a different scenario. After we observe the initial data series, I speculate about it, rather than – as in the aforementioned case – inspect my evidence and transform it in order to expand my theoretical and empirical knowledge. Suppose, I speculate that there is an additional category in *F* which I call tebsture $T = \{t, l\}$ with thready and lubricious as the feature of the material used to cut the shapes. My evidence on tebsture is empty, but it is consistent with it, in the sense discussed earlier. My further claim is that tebsture is a feature which supervenes on the observed colors and shapes in such a way that my data series becomes now: {thc, tgc, thc, lk, tgc, thc, lk, lk, thc, lk}. This corresponds to my forming new beliefs, which are not part of my evidence as the points were not observed. To capture the last data point I used my idea of square as it seemed more adequate than circle (I still lack the general notion of polygon). Next, I form a belief concerning a general regularity D(T, S) holding between tebsture and shape. Now, if I presume CRP as the random clustering process, then I will be able to forecast new data series. Of course, it will contain some anomalies like a pink ellipse or a yellow hexagon. In order to keep my original speculation, I will *rationalize* the anomalous forecasts against the upcoming evidence by adding *ad hoc* hypotheses, which would explain the anomalies for a given data series. The problems, however, will escalate with each new data series as the rationalization of D(T, S) is oriented retrospectively and is projectively futile as the speculated property of tebsture does not allow me to formulate a projection concerning for instance a new data series. The reason is that my speculation – in contrast to the earlier discussed expectation – is not based on my knowledge or transformation thereof. My speculation is an attempt at recombination of the internal and external conditions. Suppose, there is an accidental change in the mixing mechanism, so that it fails to produce mixtures containing blue, like hazel, green or violet, and instead the objects are blue all over. So, all the objects in forthcoming data series will now have the composition “bc”. According to the previous assumption, tebsture t supervenes only on mixed colors and l on basic colors. On the speculation we have a data series with lc or tbs as I lack any other way of categorizing the objects on my speculation. Both, however, lead to inconsistency. The lc category is inconsistent with my general claim D(T, S), while tbs is inconsistent with my recognition of the object shape as circle. In contrast, this kind of problem will not take place in my expectation, which would allow me to explain the relation between basic and mixed colors, and eventually to recognize the problem with the color mixing mechanism. By this argument one may thus establish that between expectation and speculation there is a similar difference as between knowledge and belief.

A more complex instance, which in contrast to the previous *explorative case* I will refer to as the *inventive case*, concerns the situation, where we no longer assume to have the complete conceptual framework F. Instead, we only recognize relevant features of objects and the categories may be conceptualized further as combinations thereof. To use the earlier example, people who enter the restaurant do not pick up one of the lunch sets from a list, but rather they freely compose their own sets by choosing any number of servings from a buffet. So, any of the group members $a_1, \ldots, a_n$ chooses any of $k_1, \ldots, k_i$ servings among those already chosen by the previous group members and then any of $k_{i+1}, \ldots, k_{i+j}$ servings not yet chosen by anyone else. Thus, every group member forms her own lunch set L_n. Like earlier, I know a general characterization of the group members F and the number of each kind of serving. I try to form a general projection concerning the assignment of lunch sets to individuals.

Suppose that my data series in this case is like the following: {{hc}, {gc}, {hc, ?s}, {hc, gc, ?s}, {gc, ?s, ??}, {hc, ?s, ?s, ??}, {gc, ?s, mc}, {hc, ?s, ??, ?c, ?c}, {hc, ?s, ??, ?c}, {hc, gc, ??, ?c, ?c}}. On my initial evidence I can recognize the features: hc, gc, mc, h, s, c. I can form simple associations as for instance hc–c. The first transformation, which aims at empirical grounding of my expectation, consists in forming a new conceptual frame F^+, containing *categories* of objects, such as color C^+ = {h, g, m} and shape S^+ = {c, s}. This phase I will refer to as *heuristics routinization* as it 1) conditions how the expectation concerning colors and shapes of objects observed is formed and 2) indicates the mechanism for generation of new values within each category, what – in turn – is indispensable for the next phase of empirical grounding.

Next, the empirical grounding like in the previous case, by the twofold elaboration of my evidence leads me to expand it with new values within each category and my ability to empirically identify them. In effect, I have: B^+ = {b, y, r, h, g, m} and K^+ = {c, s, p}. It allows me now to identify all data points: {{hc}, {gc}, {hc, bs}, {hc, gc, ys}, {gc, ys, rp}, {hc, bs, ys, rp}, {gc, ys, mc}, {hc, bs, rp, mc, vc}, {hc, ys, rp, vc}, {hc, gc, rp, vc, pc}}. The subsequent phases are follow like in the previous case, but instead of CRP I now use a different generating process to form the generalization, which is called the Indian buffet process (IBP in short). Schematically, the process is captured in the table 1.

Table 1. The IBP for the color–shape case

	hc	gc	bs	ys	rp	mc	vc	pc
a_1	x							
a_2		x						
a_3	x		x					
a_4	x	x		x				
a_5		x		x	x			
a_6	x		x	x	x			
a_7		x		x		x		
a_8	x		x		x	x	x	
a_9	x			x	x		x	
a_{10}	x	x			x		x	x

We can now modify Simonton's original model of individual creativity as follows. Figure 6 presents individual creativity as it implements CRP (Pitman 2006).

Figure 6. The explorative case with CRP

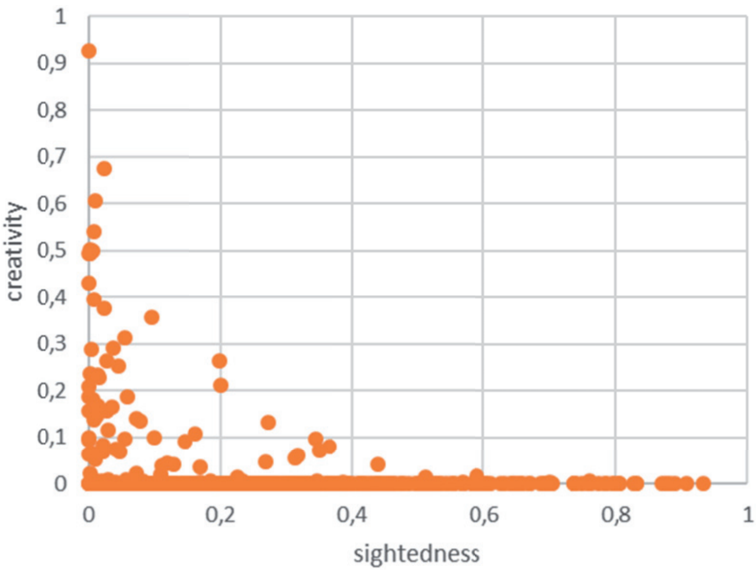
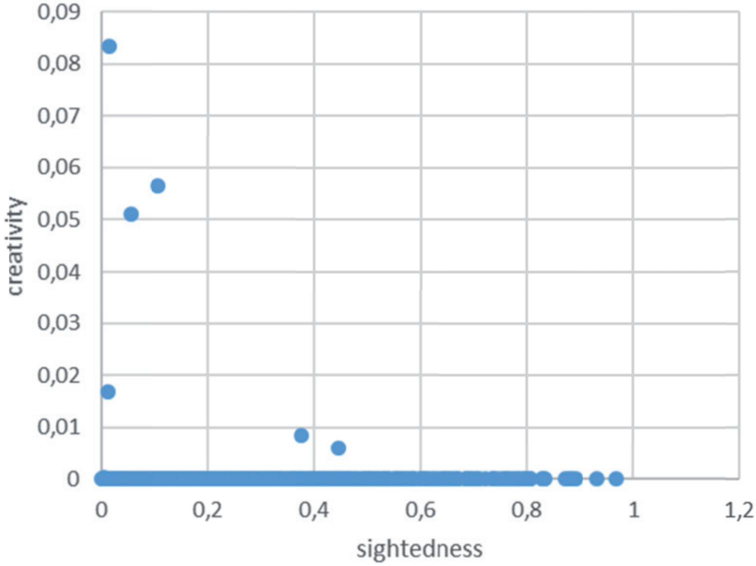


Figure 7 presents the inventive case implementing IBP.

Figure 7. The explorative case with IBP



The inventive and exploratory case constitute not only the basic options for individual choice of a researcher. We proceed now to consider how they determine collective strategies in the research community.

3. Team reasoning and the emergence of scientific routines

The heuristics-driven variation feeds into the community-level selection and retention process in scientific research. I discuss this stage using Bacharach's idea of team reasoning. This game-theoretical approach is motivated by solving the apparent puzzles of the traditional game theory as depicted in figure 8 below. Suppose we have a simple matching game, where both players get a prize if they both select the same option, while choosing without being informed about the other player's choice. For a simple choice between head and tail it might seem that the situation is like in the left panel of figure 8, where there are two equally good equilibria. It turns out, however, that the actual distribution of choices in experimental setups is appr. 80% for heads and the rest for tails. It might be interpreted that although heads and tails seem to be symmetric, heads is a more salient – or "prominent" – property. Hence, on team reasoning perspective what influences the choice is a different conceptualization of the situation. Instead of using the categories of heads and tails, the players apparently use two different categories: choose the prominent (salient) property or choose something ("choose the thing"), which is indifferent between the available options. Therefore, the model of the game is now different (the right panel on figure 8), where the choice of the salient property (e.g. heads) now becomes the only game equilibrium.

Figure 8. The role of conceptual frame in solving game-theoretic puzzles

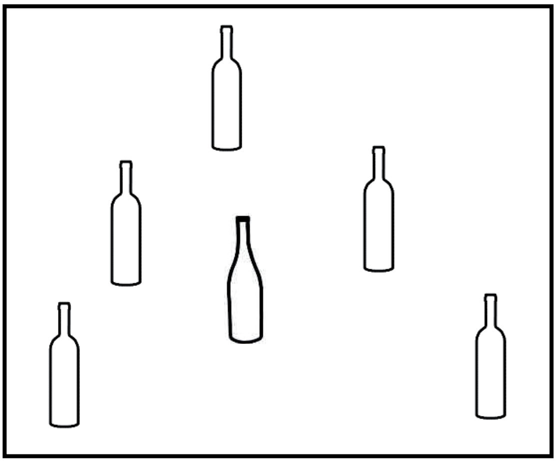
		Player 2	
		heads	*tails*
Player 1	*heads*	1, 1	0, 0
	tails	0, 0	1, 1

		Player 2	
		pick a thing	*choose the prominent*
Player 1	*pick a thing*	0.5, 0.5	0.5, 0.5
	choose the prominent	0.5, 0.5	1, 1

Source: (Bacharach 2006).

The team reasoning scheme may now be applied to a different example of 6 bottles, among which 5 have the same claret shape and one hock shape as depicted on figure 9.

Figure 9. Choice of bottles: 1 hock- and 5 claret-shaped



Source: (Bacharach and Stahl 2000).

Again, this is a simple matching game, where if both players choose the same bottle, then each receives a payoff of 1, and otherwise they get nothing. Analogously, there are at least two basic conceptualizations among the players: they may use shape concepts and partition the objects accordingly: (hock-shaped, claret-shaped), identifying the options: choose the hock bottle (h), or choose a claret bottle (c). Alternatively, they may not notice the difference and be indifferent to all bootles, while having only the option: choose a bottle (b). Figure 10 presents the pure-strategy Nash equilibria for those choices: hh, cc and bb.

Figure 10. Induced payoff matrix for the frames S (shape) and I (indifferent)

	h	c	b
h	1	0	$1/K$
c	0	$1/(K-1)$	$1/K$
b	$1/K$	$1/K$	$1/K$

Source: (Bacharach and Stahl 2000).

It is assumed furthermore that players can have models of co-players, including their frames. At the basic level 0, however, players do not develop such models, so their choices are given by a player will choose a given option o in a conceptual frame f and a given object in the selected category (Bacharach and Stahl 2000 p. 230):

$$\pi_0(o|\mathrm{f}) = \frac{1}{N_\mathrm{f}} \text{ and } p_0(a|\mathrm{f}) = \frac{\pi_0(o_\mathrm{f}(a)|\mathrm{f})}{|E(o_\mathrm{f}(a))|}.$$

So, in the bottle example the best choice for L0 palyer is h.

Level 1 players have a bias towards her own frame (for details consult Bacharach and Stahl 2000):

$$\widehat{w}(\mathrm{f}' \mid \mathrm{f}) = \frac{b(\mathrm{f}' \mid \mathrm{f})\, w(\mathrm{f}')}{\sum_{\mathrm{f}'' \in F(\mathrm{f})} b(\mathrm{f}'' \mid \mathrm{f})\, w(\mathrm{f}'')} \qquad \text{for } \mathrm{f}' \in F(\mathrm{f}),$$

$$= 0 \qquad \text{otherwise,}$$

where
$b(\mathrm{f}'|\mathrm{f}) = b$ if $\mathrm{f}' = \mathrm{f}$ and $b(\mathrm{f}'|\mathrm{f}) = 1$ otherwise.

Now, since for L0 the best choice is h, for L1 it approaches 1.

Level 2 players recognize their coplayers as is either L0 or L1 with proportion: α_0 and $1 - \alpha_0$. It generalizes to level n players, so yield the expected utility of a given option o:

$$\mathscr{E}U_n(o \mid \mathrm{f}) = \sum_{\mathrm{f}' \in F(\mathrm{f})} \sum_{o' \in \mathrm{opt}_{\mathrm{f}'}} U(o, o')\psi_n(o' \mid \mathrm{f}')\, \widehat{w}(\mathrm{f}' \mid \mathrm{f}).$$

The focal point theorem, holding for an arbitrary plain matching game, demonstrates that if it has a strong enough focal point at an object a, then a is the modal choice for players of all levels. Thus it explains the dominance of choices in a given population: "The population tendency toward the focal point combines this nonrational tendency at level-0 with rational capitalization on it by higher-level players" (Bacharach et al. 2000, p. 238).

One possible way to shift the salient option among the players is to affect the payoffs. It may be implemented by introduction of a new category of concepts Y – payoff classifier. Consider now different payoffs: match on hock pays $y < 1$, while match on claret $y = 1$.

For L1 players the expected payoffs for the two options h and c become:

$$\mathcal{E}U_1(h|\mathrm{f}) = \left[\frac{1}{K} + \frac{\widehat{w}(K-2)}{2K}\right] y$$
$$\mathcal{E}U_1(c|\mathrm{f}) = \left[\frac{1}{K} - \frac{\widehat{w}(K-2)}{2K(K-1)}\right].$$

Now, if L1 player subjective probability on the coplayer's conceptual frame is given by:

$$\widehat{w}(\mathrm{S} \cup \mathrm{Y} \cup \mathrm{SY}|\mathrm{f}) < 1,$$

then with y close to $\frac{1}{K-1}$ choosing claret bottle will be the best option. This case demonstrates one possible way to change the dominant choice for a salient option.

Figure 11. Induced payoff matrix for research strategies

		Player 2: Inventive	Player 2: Explorative	Player 2: Research
Player 1	Inventive	$\frac{1}{n!}\left(\frac{\theta\gamma}{\theta+n-1}\right)^n \exp\left(-\frac{\theta\gamma}{\theta+n-1}\right)$	0	$\frac{1}{K}$
	Explorative	0	$\left(\frac{\theta}{\theta+n-1}\right)$	$\frac{1}{K}$
	Research	$\frac{1}{K}$	$\frac{1}{K}$	$\frac{1}{K}$

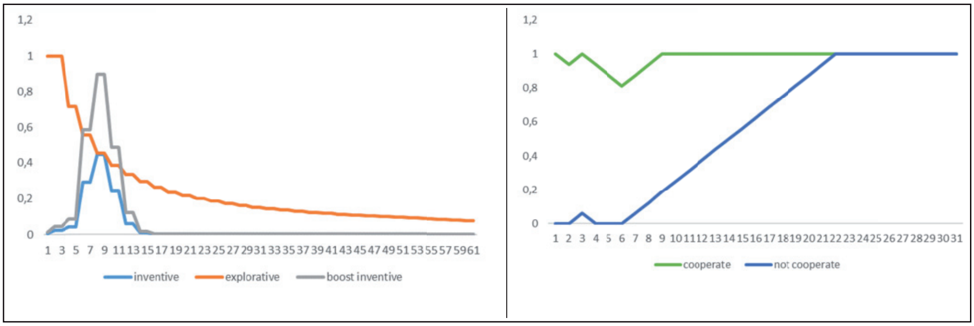
It applies to the case of scientific research as follows. Taking into account a few empirical studies on different research strategies (Foster et al. 2015, Heinze 2013) it is rather clear that of the strategies mentioned earlier, the explorative strategy is the salient option. Figure 11 presents the induced payoff matrix for the three conceptualizations of a choice of research strategy: choose inventive strategy, choose explorative strategy or be indifferent and just choose a research. In accordance with the argument presented in section 2 the probabilities in figure 11 correspond to probability distributions underlying the IBP and CRP respectively.

The change of the salient option for players may be accomplished with a possible payoff boost (ζ), which satisfies the condition:

$$\mathcal{E}U_1(\text{Inventive}|\text{f}) - \mathcal{E}U_1(\text{Explorative}|\text{f}) \sim \frac{1}{n!}\left(\frac{\theta\gamma}{\theta+n-1}\right)^n \exp\left(-\frac{\theta\gamma}{\theta+n-1}\right)\zeta - \left(\frac{\theta}{\theta+n-1}\right).$$

An agent based model (ABM) implementation of the team reasoning model of research strategy choice as reinforcement learning with transient distributions (Izquierdo et al. 2009) leads to an interesting observation presented on Figure 12.

Figure 12. Team research strategies and cooperation



Source: Author's ABM reinforcement learning model with transient distributions.

Irrespective of their initial willingness to cooperate, both players eventually decide to cooperate conditional, however, on their initial focus on discovery, either inventive or explorative. Without the payoff boost they both cooperate on explorative strategy, while the effect of the boost might only be temporal. After initial focus on explorative strategy, when they receive the boost, they turn temporarily to the inventive strategy and then continue to cooperate on explorative strategy. This seems quite rational, as the inventive stage needs some accumulated research outcomes to be successful and then – once the heuristics routinizer is identified – they explore its consequences for the available knowledge.

On the HDVSR model the critical role of boosting the inventive strategy is to generate the heuristics routinizer. As argued in section 2, it generates new scientific knowledge and is itself a precondition for advancement of knowledge by application of explorative heuristics. With the development of the standard symbolic representation for the heuristic routinizer and measurement techniques a new *scientific routine* emerges in the scientific community. Let me briefly illustrate it with a reconstruction of a recent example of the discovery of micro RNA (miRNA in short). The initial expectation was based on earlier identification by R. Horvitz of the gene lin-4, which regulates the timeline of cell fates in the nematode Caenorhabditis elegans (C. elegans in short) and published in (Ambros and Horvitz 1984). This expectation led to a series of knowledge transformations towards empirical grounding, both in terms of theoretical development and measurement capacity. Eventually, in (Lee et al. 1993) a general regulatory mechanism of lin-4 was identified. It was, however, the paper (Pasquinelli et al. 2000) that generalized the mechanism and demonstrated that is conserved evolutionally among a wide range of species. The notion of miRNa was only established in 2001, when the series of discoveries has been accommodated within the existing knowledge (Ambros 2001, Lee and Ambros 2001). The subsequent exploratory strategy focused on investigations of human miRNA and molecular regulatory mechanisms with proliferation of cancer research (Ambros 2004, Bartel 2004, Esquela-Kerscher and Slack 2006, Lu et al. 2005).

4. Conclusions

The HDVSR model sustains two basic forms of scientific knowledge generation: inventive and explorative as opposed to “knowledge” production. It also demonstrates the rationale for institutionalized intervention to retain the most valuable research outcomes – heuristic routinizers – selected in team cooperation during the research process. This was instantiated with the original reconstruction of the emergence of new scientific routine in molecular biology. However, a more elaborate ABM model would be needed to determine the realistic scale and mechanism of the intervention.

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