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KNOWLEDGE ROUTINES, THREADS AND NETWORK DYNAMICS

Abstract. The paper focuses on knowledge generation, a topic frequently overlooked in the traditional debates in epistemology and philosophy of science. We focus on investigation as the primary process generating knowledge and its products. Investigation is taken as a generalization of the research process that includes similar knowledge-generating practices in aboriginal communities. To characterize the complexity of investigation processes and their products we go beyond traditional epistemological characterization of knowledge in terms of mental states and turn to the concept of routine. Investigation processes share a common symbolic representation form which we call here a *knowledge thread*. The dynamics of the knowledge thread may be characterized by two intertwined tiers: cognitive and institutional. Using examples from our previous studies, especially on the recent discovery of microRNAs in molecular biology, we illustrate the dynamics of threads and claim that it is susceptible to the social network analysis which, however, requires insightful applications and sound interpretation of the results. Such an interpretation, as we suggest, may further be elaborated on the grounds of anthropological theories of distributed agency and distributed cognition.

Keywords: knowledge dynamics, microRNA, network analysis, projection, Kazimierz Twardowski.

1. Introduction

Evidence that knowledge grows is abundant. We use handy devices unfamiliar to our ancestors, such as computers or smartphones, more powerful than the first supercomputers. We reach out to the origins of the Universe

billions of years ago, we also identify the most fundamental particles of the matter, we produce complex objects and operate them in the outer space millions of kilometers from the Earth, we print artificial organs that successfully replace natural ones in the human body and we also arrange implausibly complex organizations that smoothly operate intricate processes on a global scale. Last, but certainly not least, the publication record grows exponentially in number. Apparently, it is not a trivial step from this observation to the assertion that our knowledge progresses. In this paper our focus is not on the latter question, but rather a related one: how this wealth of knowledge is generated.

Before we proceed with our case, a terminological comment seems necessary. Our previous concern with the dynamics of knowledge was focused exclusively on scientific research, in particular the discovery of microRNA particles in molecular biology, the story of the 1817 cholera research onwards, economic growth models and science of science studies.[1] In contrast, our considerations in this paper are intended for more generally understood shared practices aimed at augmenting knowledge, referred to here as "investigations", with research processes as a particular instantiation. What makes investigations different from our ordinary practices of inquiry, whereby we address our questions or solve problems, is that investigations contribute to the common knowledge of a given community, such as an aboriginal tribe or an invisible college, i.e., an informal scientific network of scholars. Not all inquiries or investigations are aimed at knowledge, for one, criminal investigations are primarily aimed at effective law enforcement by identifying, locating and proving the guilt of a perpetrator.

By investigations, including research processes, we have in mind inquiries that are aimed at augmenting knowledge which contribute to the common knowledge of the pertinent community. Here, we focus mostly on widely understood biological knowledge, ranging from molecular biology to ecology. Thus, investigations in this sense will be characterized by projections of the existing knowledge that are empirically grounded without, however, the presumption that any kind of instrumentation, or even artefacts, need to be involved in the latter activity.

In the present paper recurrent examples of investigations in this sense come from research on microRNAs that started in the early 1990s. We will also occasionally refer to the early cholera research and the study of the traditional ecological knowledge (TEK, in short) of the indigenous tribes of North America (Pierotti 2010). The latter knowledge is concerned with biological phenomena and may be characterized as "the ideas acquired by a human group on its environment resulting from the group's use and occupation

of a specific region over many generations" (Pierotti 2010: 9). We decided to juxtapose TEK with research processes, as with regard to knowledge-generating aspects they share the key common characteristics of projections and empirical grounding.

2. Beyond knowledge as mental state

Except perhaps for concern with its sources, the question of how knowledge is generated is often ignored in epistemological debates which focus rather on the definition and nature of knowledge. We will not engage in those debates, but at the outset of our argument we need to broadly characterize the presumed understanding of knowledge. Epistemology in the analytic tradition seems to be dominated by approaches to knowledge which try to elaborate on its tripartite characterization in terms of justified true belief. As widely recognized, this kind of approach, however, has been seriously undermined by Gettier-type of problems that reveal the dualistic predilections of this approach, and indeed its faulty compositionality.

An alternative that we take for granted here treats knowledge as the most general factive mental state, where belief and justification are derivative concepts (Kawalec 2017b). What this approach characteristically entails is that knowledge is a broad condition which depends not only on the internal state of the cognitive agent, but also on the external condition of the surrounding environment.[2]

Drawing upon a distinction between constructive and ecological approaches (Smith 2003) may shed some light on the above outlined two approaches to characterization of knowledge. Roderick Chisholm, the founder of the modern tripartite definition of knowledge, explicitly identifies its origin with Plato's rationalistic philosophy (Chisholm 1989: 90). The constructivist approach follows top-down rationality principles which are supposed to hold irrespective of the context of application. The ecological approach, in contrast, focuses on the functioning of the human cognitive apparatus which adapts to a given context. Perhaps, however, the two approaches in epistemology may be taken as complementary, as both concepts pertain to different kinds of analysis. As mentioned earlier, we focus on the ecological understanding of the concept of knowledge which pertains to our analysis of knowledge-generating processes.

Nonetheless, any of these epistemological characterizations of knowledge would be too narrow for our purposes. Following Kazimierz Twardowski's classical study on actions and products (Twardowski 1979), ad-

mittedly knowledge, as a mental state, exists as long as it is sustained by the cognizing subject. Thus, ordinarily, when we recognize that someone has knowledge, we refer to something more enduring than a currently sustained mental state, such as a disposition of this subject to generate similar mental states with a similar content. Neither of these concepts of knowledge – as a mental state or a disposition – takes into account enduring external manifestations of knowledge or its application in the design of material products or organizational processes. Following Twardowski's classical exposition of the relation between actions/states and products, we take knowledge as a product to be an external manifestation of the mental state of knowing which consists in "a new configuration, modification, or transformation of the material ... that ... had existed before the [state] began" (Twardowski, 1979: 18). This material and enduring expression of the corresponding mental state has itself causal efficacy, i.e. interacting with it leads to the emergence of a similar mental state. Therefore, while epistemologists focus on knowledge as a mental state, here we follow Twardowski's approach to knowledge in terms of enduring products.

There are three points, however, that we need to bring out here in order to complement Twardowski's original analysis for the case at hand. First, when we are concerned with an investigation, or scientific research for that matter, as this will be discussed later in more detail, knowledge – even in the sense of a mental state – may not simply be considered as a singular state of mind of an individual. Rather, it is distributed in the whole process, involving different kinds of activities such as identifying knowledge gaps and asking questions, forming expected hypothetical responses, gathering evidence and probing the hypotheses against it, as well as artefacts used throughout the whole processes such as a model, published results, laboratory notes or equipment.

Thus, the product of a completed investigation cannot simply express a singular mental state, but rather the complex underlying process that has led to this outcome. This product then will include a symbolic representation, a concept we elucidate in the ensuing, as modified by the results of the investigation, which will usually be published in academic outlets. But it will also include a number of other elements produced by the investigation routine such as skills involved in pertinent activities, e.g. a literature review, measurements, equipment handling, data coding and analysis, etc., and pertinent artefacts, e.g. data sets, laboratory notes or modifications in equipment design. Therefore, to fully comprehend, for instance, what is expressed by the concept of microRNAs as the kind of non-coding RNA particles would require much more effort, skills and complementary assets

such as laboratory equipment and software than a mere linguistic grasp of the terms in linguistic expressions of investigation results on microRNAs. As propounded by Twardowski in his analysis, we take it that the full understanding of the product of a microRNA investigation entails an ability (of a research team) to generate mental states and activities as the ones that has led to establishing this particular product. That is one reason why, for instance, in order to learn how to perform research routines laboratory training is needed, beyond mere familiarity with the published literature.

Naturally, because part of the product of an investigation routine is expressed as published results, it is possible that this part alone will be used to generate a mental state. In that case, however, the grasp of the product of investigation routine is not full but limited to linguistic (or visual) meanings of the expressions used in publications. This limited grasp does not meet Twardowski's criterion of causal efficacy as it is based on linguistic expressions, and thus will not be sufficient to retract the complete set of activities involved in the investigation routine which generated the published results. For someone who learns the concept of microRNA from publications alone having no previous laboratory training and access to laboratory equipment it will not be possible to generate the same processes that underlie this published product.[3] In order to uncover the complete meaning of the outcome of the process of inquiry or research one will need to retract all the activities that have led to this outcome, such as the apprehension of the knowledge gap in the relevant field, the rationale and conceptualization of hypotheses, research design, data collection activities, data analyses and interpretation. Without an access to relevant capacities, such as laboratory training, and complementary resources, such as laboratory equipment, that would allow this retraction the grasp of the expressed meaning will only be superficial and reduced to linguistic meaning alone. For instance, when asked to repeat the expressed outcome, the person, despite having the grasp of the linguistic meaning, will have no idea what to do. Thus, the causal efficacy that Twardowski attributes to the expressed product – in the case of such knowledge-generating process as inquiry or research – is not limited to generating a simple action or state, but instead a complex, coordinated and structured set of activities, later in the paper referred to as *routine*, that would be required to repeat the outcome.

Furthermore, the manifestation of knowledge generated by investigation will often subsequently be applied to improve the design of material artefacts or production processes in order to increase comfort, safety, efficiency or sustainability of some other activities. It is in fact this secondary kind of manifestation of knowledge that is most appreciated in non-philosophical

discourse on knowledge (Arrow 1962). For instance, when economists consider "growth of knowledge" they are interested in the delivery of new material objects such as new machines – or "capital" – exhibiting this secondary manifestation of knowledge (Beck and Witt 2019: 214; Ciborowski et al. 2019: 134). The latter, however, is not directly relevant to our present discussion as it is an application of knowledge in the design of material artefacts or production processes aimed at practical solutions and increase in economic efficiency.[4]

Secondly, as it will become more perspicuous in the ensuing, for our account the most pertinent part of knowledge as product is *symbolic representation*. It is a point explicitly addressed in Twardowski's analysis (Woleński 2016: 87) when he discusses the expression of syllogistic knowledge by means of logical symbolism of categorical sentences, e.g. *S*a*P*, etc. In that case, Twardowski claims, the logical symbols do not express the actually sustained mental state, such as an *actually made* judgment that *S*a*P*, but merely a *presented* one (Żegleń 2018: 250) whose content is grasped, but which is, nonetheless, not asserted as either true or false.

Here, however, we take one step further by making it explicit what Twardowski's analysis entails at this point. In his example of syllogistic symbolism it is taken for granted that there are four possible categorical statements of the relation between S and P by means of the syllogistic connectives *a*, *i*, *e* and *o*. When instantiated into four syllogistic figures they yield 256 possible types of syllogisms, out of which only 24 are valid.[5] With regard to syllogisms any formal discussion, or based on instantiation of the syllogistic forms, as in Twardowski's own example, is in fact framed by the symbolic representation composed of the forms of the four kinds of categorical statements and their possible combinations in syllogistic figures.

In fact, it is a general, and indeed one of the constitutive features of investigations that they use a particular kind of symbolic representation such as narratives, models or theories. Its idea presumably originated with Euclid's *Elements*, where five postulates not only expressed geometrical knowledge of the time, but they were intended to represent *all* geometrical knowledge in a condensed form. Thus, it was presumed that these five postulates entail all, or at least most, pieces of knowledge pertaining to geometry.

By *symbolic representation* we mean here this kind of condensed expression of knowledge pertaining to a given field of interest. Therefore, for TEK the symbolic representation takes the form of a story representing the origins of the world. This story represents the main ideas about the world and entails a detailed knowledge about the surrounding environment

(Allen 2021). To use a different example, the concept of microRNAs represents the biogenesis, structure and function of this kind of RNA particles. Another example is a model of economic growth which consists of a set of equations representing the most important features of the economic system. From these equations one can derive the behaviour of the agents operating in this economic system and such features of the entire system as, for instance, convergence properties of less technologically advanced systems that "catch-up" with technological leaders.

Symbolic representation, however, is not a fully specified and determined expression of knowledge. Thus, it allows for extensions and projections related to other or new symbolic representations or when confronted with empirical data other than those that served to generate this representation. We return to this issue later.

The third aspect that complements Twardowski's original analysis concerns not only the originally considered psychological, but also social causal efficacy of symbolic representation. He claims that a durable expression of a mental act or state is causally efficacious to evoke a similar mental act or state upon an interaction with the durable expression. Likewise, we claim, the durable product of an investigation routine, especially a symbolic representation, is causally efficacious to enact a similar routine. In that case, however, as mentioned earlier, some other elements will be needed, such as skills and complementary assets. In the simplest case a research team will attempt to reproduce the published results. More often, however, a new enactment of the routine will generate a new set of questions and new expectations which are based on its underlying symbolic representation. Those modifications with enactment of an investigation routine may extend the existing symbolic representation, modify it, apply it or even create an alternative one. Let us shortly consider the kind of modification which elaborates on the symbolic representation itself. This will usually happen in the early phase of formulation of the new symbolic representation when its links with the adopted body of knowledge are intensely examined; also its intrinsic elements are elaborated in greater detail and its empirical grounding is sought. For instance, after the discovery of *let-7* as the first non-coding microRNA in *C. elegans* the next step was to recognize the scope and significance of this phenomenon. With the discovery of *lin-4* and its wide evolutionary conservation in most of multicellular organisms it became obvious that microRNAs constitute a very significant concept within the regulatory mechanism of gene expression with a high potential in diagnostics and therapy of most prevalent diseases such as cancer or cardiac failures. Intense research was commenced, exploring the nature of microRNAs (e.g. its biogenesis or the

relationship with target genes), its role in various diseases and also its empirical grounding (for instance, discoveries of new microRNAs in different organisms such as humans, animals or plants). The first step, i.e. the discovery of the wide evolutionary conservation of *lin-4*, was crucial to establish microRNA as a new self-standing symbolic representation that started it as a new research thread (see Section 5 for more details). The next steps in the early years following this discovery intensely modified the symbolic representation by providing a detailed elaboration of microRNAs biogenesis or the relationship with target genes. This, in turn, led to research less focused on the symbolic representation itself, which meanwhile has matured and got an empirical grounding but rather oriented towards its application in specialized areas related to particular kinds of diseases and enhancement of the diagnostic and therapeutic potential.[6] In Section 6 we discuss how this development of symbolic representation is related to the emergence of a steadily more complex institutional network within which this research is embedded.

3. Knowledge routines

Given the distinction, based on Twardowski's analysis, introduced in Section 1 between knowledge as a mental state and knowledge as a product, we need to examine its implications for the bearer of knowledge. The bearer of knowledge is a mental state on the standard individualistic account in epistemology. For now, we leave aside the details of the structure of this mental state and also a further investigation into its metaphysical status.

In the case of investigations, as conceived of here, the issue seems more complex. According to collectivistic approach knowledge obtained in research activities is "collective" (De Ridder 2019: 7). And this, in turn, relates to three different aspects. First, it is collectively produced and "this could not have been otherwise for reasons of practical or cognitive necessity". Second, the supporting reasons, i.e. its warrant, can only be accessed by a collective "which the warrant can only be possessed and understood by a collective". Finally, knowledge has many functions, such as "stopping further inquiry", "being stored" in publications, "being available for use and applications", and "for many of these functional roles of scientific knowledge, research teams or larger collectives are the actors" (De Ridder 2019: 9–12).

However, there is an important caveat regarding the collectivist view outlined above.[7] It presumably extends the individual case to a collective one and takes knowledge as a sum of individual mental states. Perhaps

the view is implicitly more fine-grained than presented, with the possibility that some form of distributed cognition is involved and each member of the collective has only a partial access to warrant.

However, with the view of investigations as routines, the analogy with an individual mental state case no longer stands, neither in the simplistic form or a more elaborate in terms of distributed cognition. For if we follow Richard R. Nelson and Sidney Winter's line of argument (Nelson and Winter 1982), the proper analogy of a collective routine at an individual level is a skill rather than a mental state. Thus, more is involved on the part of the investigation collective than mere mental states because skills, on Nelson and Winter's account, involve also: (1) coordinated sequence of actions, (2) tacit knowledge, and (3) choices made without explicit awareness. Moreover, following this account, each team member has his own "repertoire", based on his ability to perform certain skills or micro-routines within the investigation routine, such as reviewing the literature, identifying knowledge gaps, formulation of research questions, data collection and analysis, supervision of technical equipment etc. Thus, a research team as the smallest organizational unit needs to complete all repertoires necessary for a successful investigation and, what is no less important, to coordinate them. Moreover, the team needs access to necessary infrastructure and equipment, which sometimes is re-designed to improve its performance during the investigation process. Moreover, as Nelson and Winter emphasize, the organizational context for the investigation routine frames the whole routine:

> But the knowledge stored in human memories is meaningful and effective only in some context, and for knowledge exercised in an organizational role that context is an organizational context. It typically includes, first, a variety of forms of external memory-files, message boards, manuals, computer memories, magnetic tapes that complement and support individual memories but that are maintained in large part as a routine organizational function. ... Second, the context includes the physical state of equipment and of the work environment generally. Performance of an organizational memory function is in part implicit in the simple fact that equipment and structures are relatively durable ... Finally, and most important, the context of the information possessed by an individual member is established by the information possessed by all other members (Nelson and Winter 1982: 105).

Thus, in contrast to the collectivist view, the concept proposed here, based on routines, involves far more than just a collective sum of individual mental states, as it includes also dispositions of the entire team based on their skills to perform coordinated investigation. Moreover, it includes also heterogenous elements in the emergent network: human team members with

their mental states and skills, but also artefacts, equipment and institutional context. Of these non-human elements of the network the most important is symbolic representation, as argued in Section 2.

Admittedly, all routines are, in a sense, knowledge-bearers. Take, for instance, a typical textbook example of hiring new academic staff. Typically, a part of this routine is that short-listed candidates deliver a lecture which is clearly an instance of knowledge. Nevertheless, most routines, such as hiring new academic staff, even if they involve some kind of inquiry, for instance to set up the candidate profile, are not aimed at augmenting knowledge, but at some practical aim such as an optimal decision in the process of candidate recruitment and selection. The same holds also for those kinds of learning processes, such as learning by doing, that are aimed at practical applications of the generated knowledge.

What then characterizes knowledge-generating routines? The first point has been long acknowledged in philosophy of science. Symbolic representation upon which the subsequent steps of the routine revolve is the basis of new projections.[8] Put simply, a projection is an extension of the symbolic representation which forms new conceptual links with the established body of knowledge or which extends it to new empirical phenomena. As clearly epitomized by Goodman's *grue* paradox not all projections, however, are intended to augment the existing knowledge as some are mere speculations. Again, we may recall the previous discussion based on Twardowski's analysis that the outcome of an investigation may be grasped fully, allowing thus to retract the complete routine which has led to establishing this result, or may be grasped only in its linguistic meaning. Those projections that are based on the full grasp and that are accompanied by skills and complementary assets needed to retract the full routine and by the same token constitute attempts to extend the existing knowledge are called here *expectations*. In contrast, those projections, as based on Goodman's original *grue* predicate, which are merely based on the linguistic meaning of the outcomes of the preceding investigations, are called here *speculations*.[9]

Some expectations, of course, turn out false. Therefore, the second element needed to disentangle knowledge-generating routines from others is empirical grounding. Bas van Fraassen characterizes empirical grounding in the case of physical research as the "process of simultaneously, harmoniously extending both the theory and the range of relevant evidence" which has three parts (van Fraassen 2012: 783). Determinability is related to values of theoretically significant parameters. The value of those parameters can be determined on the basis of measurement under certain conditions. The second aspect is concordance, which concerns two tiers: relativity theory and

uniqueness. Relativity theory concerns determination which is made possible by theoretically posited connections. If those values of the parameters are determined by different means, there must be concordance in those values, a condition called uniqueness. Finally, the third part of empirical grounding is refutability, which is possible only if there are alternative possible outcomes for the same measurements that would refute the hypothesis which is based on the same theoretically posited connections.

Now, the question is whether and how these three conditions apply to our general concept of investigation, whose particular instance is physical research described by van Fraassen. In order to develop a more general concept of empirical grounding which will be applicable to other kinds of research and perhaps also unequipped investigations of the common mind we turn to Raymond Pierotti's exploration of the analogies between the traditional ecological knowledge (TEK) and research knowledge. TEK is very detailed knowledge within a particular locality, and is based upon careful empirical observation. Of course, there are differences within scientific research. For instance, TEK observers "carefully store away" all the relevant information from observations rather than putting it down on paper. Hence a difference in how this knowledge is passed on. While researchers would publish their findings, present them at conferences, and perhaps train graduate students, "they would not include every detail of the activities that they employ in the field" (Pierott 2010: 12). Thus, to retract the underlying research process a research team is presumed to be equipped with necessary skills – in Nelson and Winter's terminology, to have the pertinent repertoires – and to have complementary assets which were necessary to acquire the published results, such as laboratory equipment. TEK knowledge, in contrast, is presented directly at the spot and this presentation is usually accompanied by stories of similar previous hunts.

For TEK those stories have the same function as models or theories for scientific research, namely to serve as symbolic representation:

> Thus, Indigenous stories function as metaphors that allow a philosophical framework to develop. It is not that stories are considered to be literally true, any more than models of exponential and logistic population growth are expected to literally represent the actual behavior of animal populations. Like mathematical models of population phenomena, traditional stories provide a context into which empirical observations can be placed and compared against the assumed state. TEK can be rebuilt and changed by each generation in the same way that each new generation of graduates in ecology or evolutionary biology go out and make new discoveries that add on to the base of empirical knowledge that currently exists in those fields. (Pierotti 2010: 12)

On its face, the claim that investigation is a routine may appear as an outright contradiction. Indeed, if we take the ordinary concept of routine as "automatic, low skill, repetitive, or even habitual" activity (Pentland and Hærem 2015: 466) this may seem so. But here we follow a specialized concept of routine as elaborated within evolutionary theorizing in economic sciences. This was first introduced by Nelson and Winter (1982) by analogy with individual skills.

Although Nelson and Winter provide ample characterization of routines, they do not capture their meaning in a succinct definition. This was a much later accomplishment, so here we follow the now standard definition of routine as "generative systems that produce repetitive, recognizable patterns of interdependent action carried out by multiple participants" (Pentland and Feldman 2008: 236). Now, let us turn to the question whether investigation may be characterized as routine as described in the already quoted definition. There is a long-standing tradition of methodological publications, stemming from Descartes' *A Discourse on Method* (Descartes 2006), that provide a rationale for the positive answer to this question. Notwithstanding the differences between domains and fields of inquiry, investigations recurrently follow a sequence of steps, such as formulation of questions, conceptualization of expected hypothetical answers, collection and analysis of data, interpretation of the results and dissemination. As outlined above, this sequence is also present in TEK. Each of these component activities requires dedicated skills, i.e., *micro-routines*,[10] and complementary assets to be carried out in a coordinated, consistent and systematic way. Obviously, the actual enactment of the steps involved in the investigation routine will always be unique, even in cases where it is supposed just to repeat the outcomes of an earlier investigation process, by using different data sets, data coding or methods of data analysis. Nevertheless, the whole process is structured in a similar manner by the sequence of steps outlined.

If an investigation is a routine in the above specified sense, how is it possible that it, nonetheless, generates new knowledge? Moreover, how is it possible that a research process may lead to a breakthrough in the existing body of knowledge? Even though the overall procedure is structured in a similar way in research processes, as outlined above, and many activities are highly routinized, such as techniques of data coding and analysis, or equipment supervision, each routine is enacted and thus performed with some modifications. For instance, it is constitutive of investigation processes to formulate new questions that identify gaps in the existing body of knowledge. This, in turn, entails that unique hypotheses, expressing the expected answers, are formed anew. In consequence, the interpretation of the data

would also be unique as it is oriented to verify the uniquely formed hypotheses. Each enactment of a research routine will be then different in content, most often also in performed activities, from the similar ones within the common thread. While some of these differences will lead to novel results, establishing new links with the existing nodes in the body of knowledge, and some others still will demonstrate the utility of the newly acquired knowledge, a few will significantly transform the prevalent symbolic representation and thus begin a new knowledge thread.

Various research methods and techniques are undoubtedly highly routinized elements of the research process, forming micro-routines, as they may not even have the knowledge-generating potential. Apart from these, however, the research process is constituted by such elements as conceptualization of hypothesis and their empirical grounding which characterize knowledge-generating routines.

4. Knowledge threads

Investigation processes are not isolated, but intrinsically connected. The projections, manifested in research questions and hypotheses, are based on published, or otherwise transmitted, outcomes of the preceding investigation processes. When we adopt a widespread distinction in economic theorizing, we can identify this level of analysis as *meso* which is located in-between *micro* and *macro*. In our case the micro level will refer to a study of actions or mental states of individual investigators. The macro level, on the other hand, will focus on much larger units of analysis which extend over long periods of time and thus can illuminate the turning points in the history of knowledge. Therefore, when Thomas Kuhn examines incommensurability of different paradigms, he apparently identifies them at this macro level (Kuhn 1970; Devlin and Bokulich 2015). However, when we turn to the study of meso or micro levels in greater detail (see e.g. Sady 2017), the perception of the incommensurabilities, and indeed of 'revolutionary' turns apparently dissipates and is displaced by a processualist view of a sequence of directly linked research processes (Kawalec 2020c).

Quite the reverse may happen when an attempt is made to "discover" scientific trends in relationships between subsequent investigation processes. The most prominent example is Derek de Solla Price's "law of logistic growth" supposedly governing the growth of scientific knowledge (de Solla Price 1986; Andersen and Hammarfelt 2011). Diana Crane takes even a step further to claim that this "law" is tantamount to diffusion curve

(Crane 1972).[11] However, upon careful inspection (Kawalec 2020a: 140–141), it turns out that in order to fit in the nicely drawn logistic curves the data sets in the analyses were purposely modified.

In order to capture the continuity between investigation processes and study their interrelationships over time we use the term *thread*.[12] By thread we mean a sequence of investigation processes that share the same symbolic representation. Once the concept of microRNA emerged, we can identify the development of a *microRNA thread* which is based on the symbolic representation underlying the concept of microRNA (for a detailed presentation of this thread and evidence of its stability in molecular biology – the 'mega'-thread – see e.g. (Kawalec 2018b)). Other examples of threads studied in greater detail in our earlier publications include cholera research (Kawalec 2006, 2018a), economic growth models (Kawalec 2016, 2017a), and the science of science studies (Kawalec 2019).

There are, essentially, two types of connections between investigation processes within a given thread, i.e., cognitive and institutional which correspond to the constitutive characteristics of investigations as understood here. These two aspects are intertwined as our earlier discussion following Nelson and Winter indicated. While the investigation process is framed by the symbolic representation as its cognitive culprit, the skills and assets used in the process can only be meaningful within the organization context in which they are applied. Subsequent changes in this organizational context correspond with the development of the symbolic representation.

Research processes typically start with formulation of research questions within a given area. In order to identify a knowledge gap they refer to previously completed and published research processes, so that both research questions and the projected hypotheses – as expected responses – are conceptualized in terms of a commonly shared type (in the sense of Max Weber), a model or a theory. They constitute the common core of different research processes and are referred to here as *symbolic representations*, such as microRNA, *Vibrio cholera* or Solow's growth model. For instance, the early research on microRNAs as tumor suppressor was based on the idea of the function of microRNAs in modulating their target genes. Thus, the expectation that the (mal-)function of this regulatory mechanism of microRNAs may contribute to understanding the processes of tumor formation and suppression was based on the constitutive function of microRNAs that regulate the expression of their target genes. Thus, with the emergence of the new concept of microRNAs embracing their biogenesis, structure and functions, a new thread has emerged in molecular biology. This thread is constituted by the concept of microRNAs as its symbolic representation.

The emergence of microRNA as the symbolic representation was, however, itself a long and gradual process (Kawalec 2017). Notwithstanding the differences, all these research processes that share microRNAs as the basis for conceptualizations in research questions and expected hypotheses belong to the same microRNA research thread.

Now, let us consider how those conceptual developments of microRNA affected the institutional form of microRNA research. The preparatory phase, preceding the microRNA discovery, started with initial expectations of the then unknown genetic mechanism underlying well known mutations in different cell lineages of *C. elegans*. At that time the institutional form was quite minimal within a research team at the MIT laboratory. This group split into two separate teams continuing research at two different US laboratories, and they formed a small "invisible college" (Crane 1972) of scholars interested in the same problem and communicating between those two laboratories. This continued well after the initial discovery of the first microRNA particle *let-7*. It was only upon the discovery of the wide evolutionary conservation of microRNA among the majority of multicellular organisms that a growing number of teams adopted this symbolic representation and started their own research. With the fast pace of advances in elaboration of microRNA as a symbolic representation the "invisible college" started to grow exponentially. With the growing number of outcomes of those investigations more complex organizational forms emerged such as a dedicated database of microRNA particles in different kinds of organisms, dedicated formal units and graduate programs, even dedicated start-ups and long-term research projects.

A persistent question, at least since Francis Bacon onwards, is concerned with whether a development of a given research thread represents progress, i.e. whether it contributes to enrich the existing body of knowledge. It may be easy to be misled by apparent dynamics of a thread which itself may be indicative of a fad rather than progress in knowledge. This was, presumably, the case with "laboratory cholera" research on "comma bacteria" initiated by Robert Koch, not to mention more widely known examples, such as eugenics or Lysenkoism in Bolshevik Russia. Koch's routine of plate technique, which enabled his spectacular success in identifying the cause of tuberculosis, was widely adopted by a vast number of his students and followers in biological laboratories all over Europe in cholera research. However, this ended up in a stalemate with regard to understanding cholera and in particular totally unsuccessful attempts to identify Koch's supposed "cholera poison" (Kawalec 2018a: 132–140). The "frozen" "laboratory cholera" research lasted for about next 70 years until Sambhu N. De famously demon-

strated the sought mechanism of cholera toxin by developing an alternative to Koch's routines (De 1961).

Naturally, a clear indication that a research thread progresses is the development of its symbolic representation. For instance, in the case of microRNA this included a detailed examination of its biogenesis and the regulatory mechanism of target genes in various biological processes, including oncogenesis and tumor suppression. Those theoretical developments increased empirical grounding – in van Fraassen's sense – by providing, for instance, independent evidence of the existence of microRNAs in different types of organisms.

5. Knowledge networks

The fact that a given research thread progresses, however, is only part of the story. The other part, often overlooked by philosophers of science, however, is that the cognitive progress of a research thread is intrinsically connected with its institutional development, as it was outlined above. This seems a straightforward implication of Twardowski's analysis of knowledge we proposed in Section 1. The progress of knowledge is manifested naturally in growing publication output and more complex social institutions that maintain research routines generating new knowledge. Obviously, the institutional growth should not be mistaken for rational progress, as "laboratory cholera" or eugenics remind us.

Why then turn to institutional dynamics of knowledge? One might object that since we determine whether a research thread is progressive or not, on the basis of inspection of its constitutive symbolic representation we could, as many philosophers of science actually do, ignore the institutional aspect as irrelevant. To this objection we can respond that on the view propounded here knowledge is generated in investigations, and research processes in particular, which constitute routines. Routines are mere mental exercises, but involve collective effort, interpersonal coordination and interaction and – in the case of scientific research – also the use of instrumentation. By ignoring this aspect we will fall back on the old Cartesian idea that knowledge dynamics supervenes on the internal states of a knowing agent and the generating mechanism is perhaps no more than a free recombination of ideas by the mind (Simonton 1986). In contrast, we claim that knowledge is generated in collective and structured processes of recurrent investigations where on the basis of the best of our knowledge we ask questions, form anticipated answers and confront them with empirical re-

ality. Thus, our knowledge progresses. Occasionally, we come across quite novel ideas or are struck by unexpected empirical facts. Therefore, usually we strengthen the existing thread, but occasionally form a new one; while our institutional forms reflect our progress, they also intrinsically condition it as the bearers of knowledge and knowledge-generating forms.

One way to conceptualize the institutional dynamics of research processes within a thread has been proposed by proponents of the actor-network theory. The dynamics of "dominance" was assessed relative to the expansion of a network which includes such heterogeneous nodes as humans, material objects and production processes (Latour and Woolgar 1986). This proposal, however, has at least one serious limitation: it does not allow to discriminate which of the alternative threads becomes dominant in the case of a general expansion of the whole "invisible college". If the total level of expenditure on research in a given field expands, then all networks will have a tendency to grow and the mere fact of a network expansion may simply indicate this fact, rather than its position among alternative threads.

We propose instead to rely on the tools of social network analysis that provide some helpful concepts for a detailed analysis of network expansion which can be more clearly interpreted as dynamics of knowledge.[13] Take for instance the concept of *giant component* – roughly, this is the largest component of connected nodes within the whole network. Under some assumptions, such as a common symbolic representation shared by the nodes in the giant component, the latter's dynamics over time indicates the dynamics of the whole thread, for it reflects the bottom-up clustering of the research teams around the symbolic representation to form a dominant "invisible college" within a given subfield of research.

Other examples of concepts adopted from social network analysis is *newcomer*, signifying a new node joining the network, or *average indegree* signifying the density of connections within the existing network. For instance, if it is possible to clearly relate newcomer nodes with uniquely new concepts, examination of their dynamics may reveal to what extent the thread represents breakthrough research, while average indegree may, in contrast, reveal the dynamics of novel research with a given research thread.

6. Conclusions

The results provided by network analysis may be instructive, but they need a more thoroughgoing interpretation that will shed some light on what drives the dynamics of a network. Moreover, an interpretation may turn out

to be misleading (as illustrated by Crane 1972) where the growth of knowledge represented as logistic growth curves is straightforwardly interpreted as diffusion.

As mentioned in Section 1, Twardowski's account would attribute knowledge as a product, i.e. knowledge as manifested in durable material, such as published texts, sets of equations or diagrams, or even recurrently repeated stories, with causal efficacy to re-generate mental acts or states such as the ones that gave rise to this product in the first place. For our perspective, where knowledge as a product expresses not just an individual mental state but a complex outcome of the whole routine, such as e.g. publications, skills, tacit knowledge, laboratory notes, data sets or modified equipment design, what seems more relevant is causal efficacy of knowledge as a product to retract the original routine. Hence, in order to develop more thoroughgoing understanding of the social aspect of Twardowski's analysis, one may turn to anthropological theories which elaborate on causal social efficacy of interpersonal interactions and interactions with artefacts in terms of distributed agency or distributed cognition (Gell 1998; Hutchins 2006; Enfield and Kockelman 2017). Such an account would complement the analysis presented here by accounting for various kinds of interactions in routine networks involving both humans and artefacts.

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NOTES

[1] For a succinct presentation, see e.g. (Kawalec, 2018a, 2019, 2020a).

[2] For a more detailed discussion, rationale and further references see e.g. (Kawalec 2017b, 2018).

[3] The difference between the full grasp and linguistic grasp corresponding to the whole product of investigation routine and its partial expression in publications has apparently been ignored by most of the philosophical theories of growth of scientific knowledge, such as Thomas Kuhn's theory of paradigm shifts or Imre Lakatos's methodology of research programs. They seem to overlook the difference between the linguistic meaning of the product of scientific research and their thoroughgoing meaning that allows to retract the complete research process.

[4] Kenneth Arrow's concept of "learning by doing" indicates that there is an indirect relevance to our topic discussed here, but we leave it for another occasion, as it, first, would presume the kind of analysis to be undertaken in the remainder of this paper, and

second, will drive us too far from our topic, by involving a careful delineation between "knowing *that*" and "knowing *how*".

[5] The precise number of valid syllogisms may depend on i) which of three possible interpretations of truth conditions for the connectives *i* and *o* is selected, and ii) whether there are further constraints on extensions, especially empty ones, of the terms involved.

[6] In order not to obscure the main line of argument here we deliberately omit the detailed timeline and particulars of the advances in microRNA research which have been presented in greater detail in our earlier publications, e.g. (Kawalec 2017b, 2018a, 2018b, 2020a, 2020c).

[7] Another caveat is related to causal efficacy of the product of investigation, as pointed out by Twardowski, to generate a similar action or mental state. In reply to an objection that not only a collective, but also an individual can grasp warrant, de Ridder responds that an individual will thus have a different "kind or degree of warrant" as it will be based on "testimonial knowledge". Given Twardowski's point of view, this statement seems at least incomplete. The fact that an individual will grasp the linguistic meaning of the published outcome of investigation is different from being in a position to exercise the causal capacity necessary to retract the original routine.

[8] For a detailed discussion of this concept and criticism of Nelson Goodman's original theory of projections (Goodman 1983: 84–99), see (Kawalec 2018a: 132–140). The role of projections in the social sciences is presented in (Marciszewski 2015: 20).

[9] It is doubtful that Goodman's *green* predicate would qualify as an example of an expectation as it is not seriously entertained in any investigations. In that sense the opposition *green* vs *grue* does not match the one proposed there between *expectations* and *speculations*.

[10] A well known and widespread example of such micro-routine in biological investigations is the plate technique introduced by Robert Koch in his studies on anthrax (Kawalec 2018a: 247).

[11] Diffusion curve represents transmission of information through diversified communication channels and thus, in principle, is inadequate to capture a mechanism generating scientific knowledge.

[12] Thus, we deviate from our previous publications. By introducing the concept of thread we are now in a position to more clearly capture the dynamics of investigations that share a common symbolic representation.

[13] For numerous detailed applications of the social network analysis see our earlier publications, e.g. (Kawalec 2017b, 2018a, 2018b, 2019, 2020a, 2020b, 2020c).

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