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RESEARCH BRIEF

Callon's Models of Science and Their Implications on Doctoral Science Mentoring: Adumbrating on a Contemporary Model of Advanced Scientific Training

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In one of the chapters—"Four Models for the Dynamics of Science" (pp. 29-63) —of the *Handbook of Science and Technologies Studies*, Michel Callon (1995) described four models pertaining to the nature and dynamics of science: *rational-objective (M1)*, *competition (M2)*, *social-cultural practice (M3)*, and *extended rational-objective (M4)* model. While conducting our own empirical research on doctoral science mentoring (DSM)[1] in Japan, Singapore, and Taiwan, we found Callon's work surprisingly insightful and informative in providing us with the theoretical foundation for our research. Hitherto, Callon's work remains to be a rich knowledge base for our research group to imagine hypotheses, possibilities, and questions that could improve DSM in the era of "Triple Helix" global science (Etzkowitz, in press).[2]

DSM is a public good critically important to the unbounded pursuit and sustained production of scientific knowledge, which we construe as basic, curiosity-driven, freely disseminated, and publicly owned science (Mendoza, 2012). In this essay in the sociology of science, we revisit each one of Callon's four models. We imagine their implications on DSM in an era when contemporary science is conducted simultaneously and globally in various academic, industrial, and government institutions. We conclude our essay with the argument that Callon's M4 can be appropriately applied to improve the training and enrich the socialization of future scientific knowledge producers (i.e., doctoral science students) whether their career paths are in academia, industry, or government (Etzkowitz, 2016; Mendoza, 2007, 2012; Ynalvez, Garza-Gongora, Ynalvez, & Hara, 2014).

Doctoral Science Mentoring

Mentoring has been widely utilized in business and in medicine, mainly as a strategy to increase the success rate of students entering these professions

(Barker, 2006; Eby et al., 2013; Wright-Harp & Cole, 2008). Its adoption and use in training future scientists is recent. In the general area of academic mentoring, DSM is already an understudied topic; it is also all the more understudied in the specific area of science education (Campbell, 2003; Delamont & Atkinson, 2001; Mendoza, 2007; Wright-Harp & Cole, 2008). DSM is a type of social relationship that involves activities, interactions, practices, and routines critical to doctoral students' socialization to a scientific discipline (Delamont & Atkinson, 2001; Kram, 1985; Warwick & Kaiser, 2005). Although it is possible for DSM to take on and manifest a network morphology, it is typically construed as a dyadic relationship between a senior, more experienced member (i.e., mentor, professor, or master) and a junior, less experienced member (i.e., mentee, student, or apprentice).

Typically, DSM enhances and promotes mentee's personal growth and professional development through a one-on-one coaching, guidance-oriented, and supportive relationship (Eby et al., 2013; Gattis, 2008; Kram, 1985; Hall & Burns, 2009; Ynalvez et al., 2014). Through close, collocated, frequent, and sustained face-to-face interaction between mentor and mentee, the mentor shares and transfers information, knowledge, and skills, and provides encouragement and support to the mentee. Several aspects of DSM are critical to a successful mentoring relationship: personal attributes of mentor and of mentee, attributes of mentor-mentee interaction, mentoring practices, and so forth (Eby et al., 2013; Foote & Solem, 2009; Ynalvez & Shrum, 2011). Also critical are the micro-, meso-, and macro-level social environment in which DSM is embedded and takes place.

Previous studies have shown that doctoral science students who receive mentoring support: [1] make timely progress toward their degree, [2] develop self-confidence, [3] acquire research leadership and management skills, and [4] have higher levels of research productivity than students who do not receive mentoring support (Eby et al., 2013; Darwin & Palmer, 2009; Gattis, 2008; Ynalvez et al., 2014; Ynalvez, Ynalvez, & Ramirez, 2016). In contrast, negative outcomes (e.g. delayed graduation, low self-confidence, slow progress toward degree completion, and low publication productivity) typically characterize mentees who experience poor mentoring (Eby, Butts, Lockwood, & Simon, 2004; Torregosa, Ynalvez, & Morin, 2016). While having a mentor and being in a mentoring relationship are necessary, they are far from sufficient. It is also important that a mentoring relationship is caring and supportive (Torregosa et al., 2016). These studies underscore the fact that mentoring can have positive and negative outcomes. This duality in outcomes points to the criticality and necessity of identifying and establishing best practices in mentoring.

Mentoring is never culture- or context-free (Williams, 2009); it is influenced and shaped by the larger socio-cultural context (Ynalvez & Shrum, 2011). For example, Torregosa et al. (2016) have shown that campus racial climate impacts student retention, while Ynalvez et al. (2016) have reported that the micro-level social environment (i.e., laboratory social environment) impacts publication productivity of molecular biology doctoral students. These studies illustrate how the social environment within the broader physical environment can constrain or facilitate interaction between mentors and mentees. Indeed, like any other social activities, mentoring has both a *social structural* and a *social interactional* aspect to it (Conrad & Leiter, 2013). To illustrate further, the notion of "who is a good mentor or mentee," or "what makes of a good mentor or mentee" are socio-culturally shaped by social structural forces such as organizational culture and by social interactional attributes such as frequency of interaction. Indeed, it is imperative that researchers evaluate and adjust preconceived concepts, ideas, and definitions of mentoring to account for socio-cultural influences.

Studies (e.g. Eby et al., 2013; Mendoza, 2007, 2012; Ynalvez et al., 2014, 2016) on mentoring underscore the need: [1] for more studies on academic mentoring especially at the level of doctoral science, [2] to have more cases and studies from other social contexts such as the non-West and developing countries, and [3] to delve into the consequences of mentoring on outcomes (e.g. knowledge sharing, ethics in the conduct of research, research management, scientific creativity, and research productivity). DSM is important to tacit skills acquisition in science, to increasing student retention and graduation rate, and to the quality of training of future scientists. Not so clear is which aspects of DSM—attributes of mentees and mentors, of mentoring dyads; or attributes of mentor-mentee interaction, mentoring practices—facilitate or constrain the acquisition and transmission tacit skills in the era of Triple Helix global science (Etzkowitz, 2016)? In the sections that follow, we revisit and describe the models of science forwarded by Callon, and outline a framework that can be used to address knowledge gaps in the topical area of DSM.

Rational-Objective Model (M1) and DSM

Callon's M1 embodies the classical view of science. It depicts knowledge production as rational, impersonal, objective, context-free, and exclusive to a formal scientific community. Science is construed as a special way of knowing in that neither personal attributes (e.g. ascribed, achieved, or both), emotions (e.g. envy, greed, or frustration), nor socio-cultural forces (e.g. colonial mentality, patriarchy, organizational culture) influence the production of scientific knowledge (Mody & Kaiser, 2008). For Callon, M1 portrays science as "a special and an elite" social institution where scientific knowledge derives from objective observations, accurate measurements, the straightforward exercise of cognitive skills and the application of explicit skills, and unbiased assessments of reality. Science is privileged compared to other ways of knowing (e.g. experience or tradition). It is regarded as knowledge validated by the application of universal, unchanging, and impersonal criteria that are entirely independent of and invariant to science actors' social status, personal attributes, biases, emotions, values, and "contextual situatedness" (Callon, 1995; Mulkay, 1980).

In M1, scientists are central actors, dedicatedly trained and intently committed to observing, measuring, reporting, and forwarding objective and unbiased claims and dispassionate statements (Shapin, 1995, 2008). In a way, M1 portrays scientists as monastic, disciplined, and dispassionate. Their personal attributes, life circumstances and life drama, social positions, and geographical locations are presumed and taken to not influence the content, substance, and form of statements and claims they generate and make (Callon, 1995; Shapin 2008). Scientists' tacit skills are given less focus, or not even focused on at all, because M1 presumes and takes for granted that scientific activities are accurately coded, precisely reported, and findings "unproblematically" replicated (Callon, 1995). The socio-cultural environment surrounding knowledge production and the cultural setting of scientific activities are taken as virtually having no effect on scientific work. The competencies and proficiencies attributed to scientists are solely and singularly functions of their cognitive and sensory skills (Callon, 1995). In M1, the role of codified knowledge (or explicit knowledge as articulated in diagrams, formulas, models, peer-reviewed journal articles, or research protocols) in the knowledge production and transfer process assumes a dominant and central position (Knorr-Cetina, 1999). Tacit skills (i.e., skills transferred through close interaction and by closely working together in real time and in real space) and the channels through which these skills are transmitted (e.g. mentoring, on the job training, or research apprenticeship) are sidetracked and rendered invisible.

Added to these competencies and proficiencies are a set of actions described as *rational, objective, and value-free* (Callon, 1995; Ritzer & Stephansky, 2014). According to Callon, the notion of rational, objective, and value-free action derives from science actors' capacity to make calculated, justifiable, and unbiased and dispassionate decisions such as those made using statistical decisions rules. Rules for such decisions are founded upon the efficacy of a given theoretical framework, idea system, or theoretical distribution. By efficacy, Callon meant that system's generality, robustness, consistency with empirical data, and ability to withstand rigorous testing and retesting. Overall, M1 casts the nature, orientation, and dynamics of science in the production of statements and claims resulting from the continuous work of scientists to unravel the mysteries and "secrets" of nature or the universe (Callon, 1995). Scientists aim at understanding, studying, unraveling, and transcribing nature into concepts, formulas, principles, and propositions (Mulkay, 1980). In other words, the production of knowledge is tantamount to predicting the uncertainties of nature and unraveling the mysteries and secrets of the universe through the production of models, rules, statements and propositions, theoretical distributions, theories, and idea systems (Callon, 1995).

Given this characterization of science, a number of problematic implications arise. First, M1 seems to imply that there is a monolithic and unitary model of science that applies to all contexts and to places at all times (Ynalvez & Shrum, 2015). Applied to DSM, this means that one form and style of mentoring apply to all mentees regardless of their personal attributes, experiences, and circumstances. Second, M1 with its emphasis on the actor (the scientist and only the scientist[3]) and nature (the universe) is grossly deficient in its capacity to shed light on the influence of social forces on scientific activities, development, growth, and revolutions (Kuhn, 1996). It also grossly ignores the contribution and role of doctoral students (mentees) in the production of knowledge. Third, the framing of M1 around man and nature makes it difficult to address issues concerning the role of entities that are neither man nor nature, examples of which are specimens, equipment, instruments, and technologies (Callon, 1995). Fourth, M1 views knowledge transfer completely consummated and delivered through codified and explicit knowledge, and established research protocol, and publications. M1 fails to recognize the criticality of tacit knowledge and skills, not only in the knowledge production process, but also in the training of scientists. M1 also fails to recognize that there is an aspect of science that is of craft-like dimension and logic.

Proponents of M1 imagine a doctoral science education that is mainly about acquiring codified knowledge, honing of cognitive-sensory skills, and learning to edit out the messiness of scientific work in written outputs (Delamont & Atkinson, 2001). As a platform for DSM, M1 portrays a mentoring process devoid of the psychosocial and ethical aspects of mentor-mentee relationship. Mentoring is reduced to formal exchanges, sharing of coded knowledge, following protocol, and transferring of seemingly menu-driven skills. M1 is oblivious of the human factors, the human dimension, and the human drama that go into doing science (Shapin, 2008). Furthermore, M1 does not account for the impact of socio-cultural context (both macro [e.g. national science policies], meso [e.g. organizational culture], and micro [e.g. laboratory social environment]) on science and DSM. Its focus on scientists (mentors) as focal actors leaves one wondering about the role of doctoral students (mentees) in the knowledge production process. This is especially so when scholars,—even our own research respondents—report that doctoral students constitute a cadre of elite and premium (albeit cheap and often times exploited) labor in the production of scientific knowledge (Mendoza, 2007).[4]

Competition Model (M2) and DSM

Callon's M2 casts science as the production of theoretical statements whose reliability and validity depend on the application of sound methods and standard research protocols. Within M2, Callon contends that the generation and evaluation of scientific knowledge are the result of a process of competition, an idea system that is a hybrid of Darwinian notion of struggle and survival, and Spencerian socio-biological sensibility of "survival of the fittest and elimination of the unfit". Callon describes M2 as being curiously mute about the content and substance of scientific work; it simply assumes that scientists create knowledge, which is reviewed, evaluated, and judged by other scientists (Callon, 1995). As far as M2 is concerned, knowledge is transmitted in the form of publications disseminated without any restriction or extrinsic considerations such as those that pervade private profit-oriented science. For Callon, this perspective assumes that scientific knowledge is acquired and transferred explicitly and unproblematically through codes, diagrams, formulas, manuals, monographs, and written protocols. This implies that the existence and role of tacit skills in knowledge production are less important and receive lower priority vis-a-vis codified knowledge (Collins, 2010). In other words, M2 fails to recognize that scientific knowledge has explicit and implicit, manifest and latent, and spoken and unspoken dimensions.

In the context of M2, the actors involved in knowledge production are the scientists themselves, and a mindful distinction is made between scientists (or experts) and laypersons (or non-experts; Callon, 1995; Epstein, 1996). In a way, there is an implied boundary—real or imagine—that marks the difference between insiders and outsiders to the scientific community (Epstein, 1996), and a system of gradation distinguishes and stratifies knowledge workers in terms of their education, experience, skills, and training. Although other actors such as research associates, research assistants, and lab technicians are not ignored, Callon contended that they are seemingly reduced to mechanical, instrumental supporting roles. Callon posited that although scientists are seen as social actors, their individual competencies and training are not analyzed, defined, or examined. Their involvement and membership in a scientific domain (e.g. physical chemistry) determine their objectives and goals, together with their theoretical orientation and experimental approaches. Hence, for Callon, the objectivity and rationality of scientific activity results from the rational interactions among scientists, particularly in their competition, and not from any defining native traitor proclivity that set them a breed apart from other people and social groups.

For Callon, M2 is rested upon the processes of growth and development; processes that are fundamental to the Darwinian, the Spencerian, and the neoclassical economic framework. In M2, the advancement and progress of science are explained by the fact that scientists work in research areas where there are yet unexplored and uncharted sectors (i.e., knowledge gaps), where the symbolic returns (i.e., prestige and recognition, which are intrinsic to academic science) are most likely because the puzzles or knowledge gaps being addressed are considered important, either economically, politically, or both (Callon, 1995; Kuhn 1996). Indeed, the very notion of competition in M2 implies a monolithic and unitary objective of science that all scientists—within a scientific domain—in various contexts and places aim for. M2 and M1 intersect; however, unlike M1 though M2 adds emphasis on extrinsic aspects such as the economic and the political as they apply to the scientific (Jasanoff, Markle, Petersen, & Pinch, 1995; Shapin, 2008). The market-like behavior of academics and of universities, as they aggressively compete for grants from public and private science foundation such as the National Science Foundation, and the Spencer Foundation is a case in point (Mendoza, 2007).

Similar to M1 and by implication, M2 casts doctoral science education as mainly the acquisition and transfer of explicit knowledge. It also casts the training of future scientists as the application of the scientific method in the pursuit of universal goals through a process and type of conflict-like competition akin to one described by Randall Collins as micro-level conflict (Ritzer & Stephansky, 2014). In a way, M2 seems to trivialize the role of tacit knowledge and skills in doing science. It is silent about the role of non-competitive activities such as research collaboration and professional networking in the production of knowledge (Aguilar et al., 2013; Ynalvez & Shrum, 2011). Moreover, while M2 alludes to some form of "secretive norms" in science or "manifestations of territoriality" that derive and result from competition (e.g. race to publish first), M2 does not mention deviance and ethics in the conduct of research. All that M2 states is that there is competition, but it does not speak about its link to scientific misconduct, or the possibility of deviant behavior in science and in doing science. M2 also does not put premium on the role of mentoring (e.g. apprenticeship) and other informal practices (e.g. social networking) in the making of a scientist. It takes for granted the messiness of science and the trial-and-error experiences critical to the honing of scientific artisanship and in doing science (Delamont & Atkinson, 2001).

Socio-Cultural Practice Model (M3) and DSM

M3 frames science and its actors as no different from any other social activities (e.g. production process in a factory) and other social actors (e.g. factory workers). There is nothing special or sacred about science and scientific life, and they are subject to shifting logics, priorities, sensibilities, and values (Callon, 1995; Knorr-Cetina, 1995). M3 characterizes science as fluid, tentative, inherently uncertain, messy, and unpredictable (Delamont & Atkinson, 2001), always contentious, never ending, and most of the time problematic. Imagined within M3, science is a local and mundane activity. It is sufficiently accounted for and described by ordinary human learning capacities, and by ordinary forms of social interaction and social exchange (Callon, 1995; Shapin, 1995). Callon argued that while M1 focuses on statements and the meanings inherent in the system of concepts, statements, and rules regardless of context, M3 posits that concepts, data, statements, and rules are meaningless and disembodied without context and place—*context and place matter* (Shrum, 2005).

Put another way, this perspective considers and stresses the contextual situatedness of science—the social shaping of science (Shapin, 2008). It bestows importance and recognizes the role of tacit knowledge and skills in doing science and in producing knowledge (Bowden, 1995; Collins, 2010; Knorr-Cetina, 1995; Mody & Kaiser, 2008; Shapin, 1995). M3 further contends that certain forms of knowledge cannot be expressed in the form of explicit statements or codified knowledge (e.g., formulas, published research protocols, technical manuals, and textbooks). This implies that science is an activity that depends on localized knowledge, specific "tricks of the trade" (Leahey, 2006), and rules that cannot be transmitted explicitly (Collins, 2010; Delamont & Atkinson, 2001; Shapin, 1995) unless actors are mentored and socialized to the practices of a particular disciplinary domain through close, frequent, and sustained face-to-face interaction (Delamont & Atkinson, 2001; Rammert, 2006).

In contrast to M1 and M2, knowledge producers are not limited to or focused on scientists themselves. Aside from research assistants and laboratory technicians, Callon contended that the list of other actors and identities depends on the specific context and situation under study: corporations, firms, manufacturers and distributors, media personnel, government agencies, funding agencies, and external pressure groups (Bijker, 1999; Collins & Pinch, 1998; Epstein, 1996). M3 sees the boundaries of science as constantly evolving and shifting. These boundaries, real or imagined, are continually contested and negotiated (Gieryn, 1995). This is obvious in the increasing convergence—whether asymmetrical or not (Smith-Doerr & Vardi, 2014) or not (Mendoza, 2012) —between academic and industrial science (Etzkowitz, 2016).

In M3, actors involved in the production of knowledge can be individuals and/or organizations and not necessarily from within the scientific community (Callon, 1995; Epstein, 1996; Mulkay, 1980). Indeed, knowledge production is an open system that obtains inputs and material needs from the larger socio-cultural context and environment wherein it is embedded. In the casting of M3, the mechanisms by which constraints, demands, and interests outside the scientific community influence the generation and production of scientific knowledge are analytically important to examine (Callon, 1995). For example, how are the norms of unconditional sharing of knowledge and materials morphed by academic scientists' involvement in industrial science is a case in point (Shibayama, Walsh, & Baba, 2012). Or how doctoral science mentoring practices evolve in terms of content, delivery, and form when academic scientists engage industrial counterparts and activities (Mendoza, 2007, 2012)?

According to Callon (1995), knowledge producers' (i.e., scientists, technicians, assistants, etc.) competencies are diverse and include the capacity to not only formulate and interpret codified statements and algorithms, but also to elaborate, control, elaborate, and transmit tacit knowledge and skills. M3 rests on the assumption that scientific actors are capable of learning and creating. Callon posited that this capacity to learn (and learn from experiences and interactions) and create (often times pervaded by trial and error) endows them with both historical depth and ability to invent, which enables one to see why science might not be limited to mere repetition and replication (Callon, 1995; Collins, 2010). The heightened emphasis is on tacit knowledge and skills, and on the mechanisms of learning and creating leads to the emergent understanding that science actors constitute a social group with its own informal and idiosyncratic practices, and ways of doing (Callon, 1995; Collins, 2010; Shapin, 1995).

Callon (1995) is of the thinking that interaction can only develop and thrive within the context of a shared culture, and scientific activities are not exempt from either the disabling or the enabling power of the shared culture of a social group. In Collins' (2010) idea system, the "core set" is the basic and fundamental social group responsible for the production and dissemination of scientific knowledge. In Crane's (1972) idea system though, that core set does not have the logic and morphology of social groups, but that of social networks. The dynamics of these social networks in science depend on the strategies network members utilize in building and strengthening ties (Callon, 1995). M3 aids in the imagining of scientific relationships and knowledge production as having both a group and a network dimension such as those that manifest in research work groups and collaborative research networks.

M3 casts doctoral science education as about the acquisition and transfer of tacit knowledge and skills; in a way, attenuating the celebrated central role that M1 and M2 bestow to explicit knowledge and to cognitive-sensory skills. M3 claims that much of creating and learning involves social interaction with both experts and non-experts in the context of a social group (Callon, 1995). Furthermore, it recognizes the "embeddedness" of doctoral science training within the larger socio-cultural context, but at the same time tends to sidetrack the influences of economic and political forces. In a way, M3 is mindful of both the social shaping of science from both the macro-level social structural and the micro-level social interactional.

At the social structural level, M3 allows one to imagine how societal norms (e.g. authority, reciprocity, sharing, etc.) and cultural factors (e.g. language, religion) might shape the organization of doctoral science training. At the social interactional level, M3 allows one to envision how personal attributes (e.g. age, gender, ethnoracial identity, training, etc.) of mentors and mentees might influence the dynamics of mentoring together with the content and form of mentor-mentee interaction. M3 also allows one the opportunity to muse how, for example, bases of social inequality (i.e., age, ethnoracial, and gender) work to facilitate or conspire to constrain the transmission of tacit scientific skills. It also affords the opportunity to examine how the impact of social interactional (local and micro) dynamics on DSM is conditioned by social structural forces (global and macro).

Extended Rational-Objective Model (M4) and DSM

Callon (1995) asserted that M4 is a hybrid of M1 and M3. Consistent with M1, this eclectic model portrays scientific work as generating claims, producing statements, and establishing relationships among statements (or generating propositions). Like M3, however, this hybrid perspective focuses on *the process* of knowledge production; it also emphasizes the central role of tacit knowledge and skills in doing science and in the scientific research process (Callon, 1995). In contrast to M1, which focuses on concepts, claims, statements, rules, and propositions, M4 is an extended version of M1 because it also focuses on all operations that link claims, statements, propositions, technical devices, and human actors (Callon, 1995).

In describing M4, Callon introduced the idea of *translation*, which he argued as central to the production of claims and statements. For him, translation is the collection of all interactions among codified information, technical devices, and tacit knowledge and skills that result to the production of claims and statements; and when brought to interact with human actors, translation leads to *translation networks* (Callon, 1995). Callon described translation networks as aggregations of reality wherein claims, statements, technical devices, tacit skills, and human actors are brought together to interact among each other. That said, translation networks are akin to Bijker's (1995, 1999) concept of *socio-technical ensembles*, which describes a heterogeneous network of human and non-human actors (Pickering, 1992). Callon contended that doing science generates translation networks mainly through its ability to create and alter entities in the natural and the social world.

In M4, the notion of an actor is subsidiary to the more generic concept of an *actant* (Pickering, 1992), which refers to an entity that has the ability and the capacity to act (Callon, 1995; Latour, 2002). For Callon, that ability and that capacity to act may reside in a claim, a statement, a technical artifact, a tacit skill, or a human actor who creates statements and constructs artifacts. Within the bounds of M4, and by its allusion to "human actors," it is logical and sensical to construe actants as either human or non-human actors (Pickering, 1992). Indeed, the notion of an actant is insightful in the study of scientific work because doing science continuously morphs the list and the definition of entities (or actants) that make up the physical (e.g. atoms, molecules) and the social (e.g. Facebook® friends, e-collaborators) world.

Callon (1995) posited that the idea of translation networks—which we argue captures the realities of contemporary globalizing science—renders the "man-nature" (or social reality-physical reality) distinction and the "macro-micro" (or global-local) conceptual bifurcation archaic and old fashioned. Indeed, Callon›s idea of translation networks allows the conceptualization of a continuum—a spectrum—(a) between active, subjective social reality and passive, objective physical reality, and (b) between the micro-level social interactional (local) and the macro-level social structural (global) dimension. As such, this continuum affords a space for a middle ground, a socio-technical ensemble (Bijker, 1995, 1999), inhabited by actants—human and non-human, individual and supra individual (e.g. organizations)—whose competencies and identities evolve with the very translations transforming them (Callon, 1995; Pickering, 1992).

Callon (1995) keenly identified three properties of translation networks—*irreversibility*, *lengthening*, and *diversity*—and clearly asserted that these properties obscure the *macro-micro* and the *man-nature* distinction. He defines *irreversibility* as the extent to which translations are consolidated, which make further translations necessary, predictable, and unavoidable. Under such conditions, actants become highly interconnected, densely packed, and complementary such that the boundary between the macro (or global) and the micro (or local) becomes blurry.

The *lengthening* property of translation networks pertains to the increasing number of diverse actants, which eventually leads to "black-boxing," wherein entire lengths of translations are folded, encased, and embodied in technical devices, in chemical formulas, and even in tacit skills (Callon, 1995). The *diversity* of a translation network pertains to the interconnectedness of a system wherein many diverse and disconnected networks imply myriad translations (Callon, 1995). Diverse translation networks extend deep into and zero-in the micro (or the local, such as a specimen or a scientist in lab) level and stretches far out to the macro (or the global, such as transnational science policies) level in ways that the global is in the local, and the local in the global.

All three network attributes open an avenue for the characterization and study of socio-technical ensembles as they relate to the transmission of tacit skills, DSM, the globalization of science, and the emergence of new technologies such as information and communication technologies (ICT). That avenue inspires new research questions to be asked and imagined. For example, does ICT utilization lead to interdependence and complementarities in scientific practice and in DSM between developed country and developing country knowledge production systems? With ICT, what new actants come into play in science and in DSM? How do ICT morph the nature and the structure of mentoring relationships? How do the increasing interactions between science actors in various science sectors (i.e., academia, industry, and government) and across disciplinary domains influence DSM and the norms and values of science?

Clearly, M4 frames doctoral science education as simultaneously characterized by the acquisition and transfer of explicit (codified) and implicit (tacit) knowledge, and of cognitive-sensory skills and tacit skills. M4 helps us recognize that learning entails both formal (e.g. the course work that is signature of doctoral science training in the United States) and informal (e.g. apprenticeship, mentoring, and hands-on-training) aspects, and through interaction with experts and non-experts, with human and non-human actants. M4 also assists us in the visualization of DSM relationships that combine both the logic of mentoring groups and mentoring networks, and perspectives of collocated and non-collocated human actors. Furthermore, M4 helps us recognize the influence of macro-environmental factors (i.e., cultural, economic, political, and social) on science and scientific training.

Adumbrating a Contemporary Model of Science

Based on these descriptions of Callon's models of science, we argue that M4 provides a comprehensive framework to the further understanding of the knowledge production process and DSM practices in the era of Triple Helix global science (Etzkowitz, 2016). As an eclectic of M1 and M3, M4 accounts for the emergent features of global science and DSM such as:

[1] The evolving global actants, forces, institutions, and processes resulting from ICT's capacity to alter the spatial, temporal, and social aspects of interaction in science through high-speed and multi-way communication and information exchange;
[2] The alterations in knowledge production ushered in by ICTs, which enable the formation of translation networks such as e-collaboration, e-mentoring, open-access publishing, big data, and the transmission of skills through ICT-mediated interaction and networking;
[3] The social shaping scientific institutions and practices within the larger socio-cultural system, which are shaped by competing values and interests along the local-global continuum, and by social forces that emerge from the meshing of the social interactional, the social organization, and the social structural levels (Conrad & Leiter, 2013);
[4] The heightened influence and active role of trans-epistemic actants (human and non-human) located inside, outside, and at the boundaries of science—even those that are at the intersections of scientific sectors—which underscore the steady integration and meshing of activities, engagements, roles, sensibilities, and ethics and values across sectors of science locally and globally (Etzkowitz, 2016);
[5] The increasing awareness about the salience of tacit skills in knowledge production, and the realization that such skills can be transmitted via high-quality real-time ICT-mediated interaction and professional networks (Collins, 2010); and
[6] The evolving morphology of scientific organizations into a form that combines the logic and sensibilities of local scientific groups with those of global scientific networks (Ynalvez & Shrum, 2011). At the social interactional level, this implies that the morphology of DSM relationships may shift from traditional dyadic models of mentor-mentee pair to collaborative or network forms of mentoring. At the social structural level, this implies that DSM shifts toward relationships and networks at the intersection of the various sectors of science (e.g. academic and industry) located at the core (i.e., developed countries) or periphery (i.e., developing countries) of the global scientific system.

Mindfully considering these features of Triple Helix global science enables the setting of policies and the development of training regimes that stand to the challenges and realities of science and doing science in the 21st century.

Notes

1 We are intentional in using the phrase "doctoral science mentoring" because we focus on doctoral mentoring in the biological and the chemical sciences.

2 The Triple Helix perspective casts scientific knowledge production process as happening in three sectors: academia (in university research labs), industry (in industrial research and development labs), and government (in national labs). This perspective posits that scientific knowledge is increasingly processed and produced at the intersection of these sectors, which results to a transmutation of science itself -- its actors, dynamics, ethics, norms, sensibilities, and values (Etzkowitz, in press).

3 Again, who is a scientist? In our experience interviewing scientists in Africa and in Asia, there was not a unitary and monolithic response to this question. In our home university, a scientist would be a full-time faculty, either tenured or on tenure-track, a Ph.D., teaches undergraduate and graduate courses, publishes articles in peer-reviewed journals, conducts curiosity-driven research, and attempts to secure research grants from

agencies such as the U.S. National Science Foundation, and other foundations.

[4] Postdoctoral fellows (postdocs) also comprise the cadre of premium labor force we mentioned. In our interviews with scientists and students in East Asia, doctoral students reported that postdoc were from whom they learned about the techniques needed to do techno-scientific work.

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