Scientific and Technical Human Capital:

An Alternative Model for Research Evaluation[*]

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Abstract:

We provide an alternative model for evaluating science and technology projects and programs. Our approach, a "scientific and technical human capital" (S&T human capital) model, gives less attention to the discrete products and immediate outcomes from scientific projects and programs- the usual focus of evaluations- and more attention to scientists' career trajectories and their sustained ability to contribute and enhance their capabilities.

S&T human capital encompasses not only the individual human capital endowments but also researchers' tacit knowledge, craft knowledge, know-how. S&T human capital further includes the social capital that scientists continually draw upon in creating knowledge—for knowledge creation is neither a solitary nor singular event. In sum, it is this expanded notion of human capital when paired with a productive social capital network that enables researchers to create and transform knowledge and ideas in ways that would not be possible without these resources. We review literature contributing to a S&T human capital model and consider some of the practical data and measurement issues entailed in implementing such an approach.

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1   Introduction

An enduring strength of US science and technology policy over the five decades since war ended its more laissez manifestation, has been the great diversity and sheer magnitude of government research and development (R&D) programs and investments. These programs have amassed over time to include a broad range of objectives, procedures, and designs—some intramural, others extramural; some large, some small; some academic, some industrial; some fundamental, others applied.   Their missions and modes of operation are myriad.   While this amorphous collection has yielded rich and diverse habitats for the growth of science, it has also provided policy analysts with a well-stocked laboratory for the development of tools to evaluate R&D programs and policies—at least, that is, in principle.

Despite such inducements to innovation in evaluation practice, advancements in techniques for evaluating scientific research have been slow to come. For scientists themselves, the one area of R&D evaluation policy that has historically enjoyed strong support has been the inclusion of peer advice in making grant proposal funding decisions within individual agencies and programs.   In fact, the principles of peer review have become so engrained in the cultures of science agencies—such as the (United States) National Science Foundation and the National Institutes of Health—as to have become rigid in the eyes of some [1,2,3].   Arguably, the rise of the peer review model and

strongly held beliefs in the sanctity of the individual investigator approach have eroded willingness within the scientific community to consider non-peer-based R&D evaluation approaches. Moreover, new developments in government accountability and performance requirements ensure that peer-based evaluations will need to be supplemented by approaches providing discrete and more "objective" evaluation results. The U.S. Congress passed the *Government Performance and Results Act of 1993* [4], mandating periodic evaluation for all federal agencies and programs, even science-based ones. This has set off a heated debate about science and technology program evaluation, a topic heretofore restricted to remote channels of academic discourse.

Several approaches have developed as alternatives to peer-based methods for evaluating science and technology (see Bozeman and Melkers [5] or Kostoff, Averch, and Chubin [6]for an overview). Most of these have simply been adapted from other fields of evaluation, fields with a more long-standing tradition. In the United States, professional evaluation of science and technology policy has been dominated by microeconomic models and their attendant tools, especially benefit-cost analysis. These approaches have a strong appeal, focusing as they do on discrete science and technology outputs such as the number of articles or patents produced in R&D projects, jobs created by technology transfer programs, and contributions of technology-based economic development programs to regional economies. Evaluation rooted in neoclassical economics seems to hold forth promise of "harder" more rigorous analysis and, thus, matches well the policymaker's need for justification of expenditures. Rationalist, "new public management" approaches to government performance, such as is embodied in the

Government Performance and Results Act, seem quite compatible with evaluation based on microeconomic models, yielding a monetary value.

While economics-based approaches often prove useful, the focus on the discrete products of R&D projects places significant limitations on evaluation. In the first place, the fact that such approaches work best when there are crisp boundaries (e.g., a single R&D project) is itself a major limitation. Second, the tendency to have science and technology products disembodied from the individuals and social context producing them provides an unrealistic overlay to evaluation. Third, such evaluations tend to be static. To be sure, many cost-benefit studies model streams of benefits over time but they rarely take into consideration the mutability of the "products" evaluated, much less the changes in the persons and institutions producing them. Fourth, product-oriented evaluations tend to give short shrift to the generation of capacity in science and technology, and to the ability to produce sustained knowledge and innovations.

Our goal in this paper is to provide an alternative model for evaluating science and technology projects and programs. Our approach, a "scientific and technical human capital" (S&T human capital) model, gives less attention to the discrete products and immediate outcomes from scientific projects and programs and more attention to scientists' career trajectories and their sustained ability to contribute and enhance their capabilities.

S&T human capital encompasses not only the individual human capital endowments normally included in such models [7,8], but also the sum total of researchers' tacit knowledge [9,10], craft knowledge, and know-how [11]. S&T human capital further includes the social capital [12,13,14,15] that scientists continually draw

upon in creating knowledge—for knowledge creation is neither a solitary nor singular event. In sum, it is this expanded notion of human capital when paired with a productive social capital network that enables researchers to create and transform knowledge and ideas in ways that would not be possible without these resources. Before elaborating out model, we first turn to a brief discussion of the assessment of knowledge and its value which begins to lay the groundwork for our model.

2   Research Value

Historical disagreement over which evaluation tools are best suited to measure the value of R&D outputs and outcomes stems more from *what* is measured than *how*. All of the commonly used modes of R&D evaluation—economic analyses (e.g., Link [16,17,18]); counts of scientific outputs such as published works, citations, patents, and awards (e.g., Cozzens [19]); peer judgment (e.g., So [20]); and historical case analyses (e.g., ITT [21])—have come under fire for one reason or another at one time or another.

Economic approaches have been criticized for not effectively capturing the totality of scientific outcomes. And, in many instances, economic valuation does exclude uses of knowledge that are not easily captured by markets and their pricing mechanisms [22]. No matter how valid and reliable are the methodological and analytical means, such as cost-benefit analysis, some dimensions of value are inevitably shortchanged [23]. Scientists intuitively understand this when they dismiss such studies as underestimating some of the most important aspects and implications of their work. Furthermore, economics tends to treat much of the product of science as an externality, a spillover, or

as a market "failure." The conception of knowledge in such terms is indicative of the mismatch between neoclassical economic theory and knowledge value theory, of the *ignus fatuus* of the market paradigm as applied to science, and of the raw difficulties inherent in the act of measurement.

State-of-the-art valuation often exists as a counterpoint to economic valuation. This approach, usually peer-based, may be effective in benchmarking some scientific output or the development of a technology, but it is not particularly strong at illuminating use and the implications of use toward social and economic ends. State-of-the-art assessments often make use of bibliometric analyses of various types[24]. The principal advantage of these approaches is in measuring the productivity of scientists [24]. Although attempts have been made to address quality *qua* productivity, bibliometrics generally falls short on this criterion. Finally, while historical case analyses may provide rich insights into the process of knowledge creation and its longer term outcomes, they often fail to generalize in ways useful to more global-scale policymaking [19].

In general, these evaluation methods tend to be too narrow in defining the unit of analysis and far too limited in defining their outcomes—focusing generally on either a monetary translation of scientific and technical outputs or the outputs themselves. It is not what is in these methodologies that is the problem, it is what has been left out. What is needed is theory that incorporates these points directly into the evaluation model, not as patchwork afterthoughts.

In recent research on the social and economic effects of R&D projects supported by the US Department of Energy [25,26], we came to the conclusion that all of these R&D assessment methodologies lack recognition of the socially-embedded nature of

knowledge creation; transformation and use; and the dynamic, capacity-generating interchange between human and social capital. On this point, Zucker, Darby, and Brewer [27] found, in studying the growth of the biotechnology industry, that the industry has grown up literally around so-called scientific superstars of the field [28]. It was investments in basic R&D—many of which were supported by the federal government—that led to start-up firms that clustered geographically around universities where these biotech superstars worked. The human capital capacity generated by government investments led to the economic wealth. But, in funding those projects, the government was not making *financial* investments, but *scientific capacity generating* ones. Arguably, then, public R&D evaluation should center not on economic value or even improvements in state-of-the-art, but on the growth of capacity [23].

While analytically and practically more difficult, the most important capacity questions pertain not to individuals or research projects but to entire communities [29,30,31,32,33,34,35,36]of researchers, technologists and users of scientific and technical knowledge. In the *Research Value Mapping* project, our case studies of scientific projects helped us to develop the concept "knowledge value collectives." A knowledge value collective is a set of individuals connected by their uses of a particular body of information for a particular type of application [37,38,39]. It is a loosely coupled collective of knowledge producers and users (e.g., scientists, manufacturers, lab technicians, students) pursuing a unifying knowledge goal (e.g., understanding the physical properties of superconducting materials) but to diverse ends (e.g., curiosity, application, product development, skills development). The "value" of the knowledge can be equated with the range and intensity of uses to which it is put.

With respect to S&T human capital, the primary task in public support of science and technology is to develop and nurture the ability of groups (whether networks, projects, or knowledge value collectives) to create new knowledge uses, not simply to develop discrete bits of knowledge or technology.

3   Scientific Careers, Human Capital, and the Life Cycles

Life cycle models [40,41] view the careers of scientists as a longitudinal function of individual skill levels and various incentives and disincentives to act productively, as mitigated by the effects of human aging [42,43]. The concept of a career life cycle originated in human capital theory from an economics tradition that dates to the late 1950s [44] [45].   Human capital theory sought to relate investments in human beings (education, training, job and life experiences, personal health[46]) to an individual's earnings trajectory.   In brief, the theory posits that at younger ages, individuals will forego short-term earnings from immediate work in favor of the longer-term potential wage gains derived from additional years of schooling or from other forms of training [45,47,7,48,8,49,50,51].   As an individual—who is assumed to act in utility maximizing ways—grows older, the combined effects of age and ever more truncated career time horizons act to curtail additional human capital investments and so declines productivity.

In the scientific life cycle model, Stephan and Levin [52] [53] report that scientific productivity, usually measured in publication or citation counts, follows one of two general patterns (depending on scientific discipline): "those in which output declines with age and those in which output initially increases with age and then eventually

declines" (p. 50). Although there is empirical evidence to support this notion of diminishing marginal rates of productivity[54], there is also suspicion that perhaps more powerful forces than age may be at work. In short, such models fail to explain much variation in productivity [55], and a multitude of potentially spurious causal effects have not yet been ruled out. Stephan and Levin argue that what is lacking in these models is attention to the research process and the institutional setting of the process [52]—something, incidentally, more akin to S&T human capital.

In human capital theory, both Becker and Schultz recognized the role of scientific research in human capital formation. Schultz [49] saw scientific research and education as "industries" that produce new forms of capital themselves. He asserted that scientific research yields two forms of capital: that which is transformed into *new skills* and human capabilities of economic value (human capital), and that which is transformed into *new materials* of economic value (nonhuman capital). Becker [48,56] argued that growth in scientific knowledge has raised the productivity of labor and increased the value of education and training as embodied in scientists, technicians, managers, and other workers.

What is missing from human capital theory and life cycle theory, however, is recognition of the full range of resources and behaviors that workers bring to their work, or in our case, scientists bring to their collaborations. Unfortunately, for the most part, human capital theory has not advanced far from its origins that were laid out in the early works of Becker, Schultz, Mincer, and others (see Sweetland [57] or Marginson [58]). Indeed, further theory development has been passed over by scholars in favor of empirical studies that most commonly operationalize the concept as years of education or

years of work experience and relate education to broad trends of productivity in the economy. According to Nordhaug [59], human capital theory still comes up conceptually short:

> The *substance* of human capital has been treated predominantly as a black box, although rough distinctions between investments in education, training, immigration, and health-related measures have been drawn. However, it is basically the substance of the *means of generating human capital*, rather than the substance of the human capital itself that has been discussed (p. 19).

We agree. In human capital theory, it is fair to say, that the human being is regarded as a knowledge delivery mechanism into which inputs are added in the form of education and training and outputs are received in units of productivity, higher earnings, and expanding economic growth. It is the emphasis on the *value* of knowledge creation, recombination, transformation, and application process that is missing. The process that takes place within the black box is inherently social, it can be called capacity generated by S&T human capital, and it is missing from theory.

With that said, how can human capital theory be tailored to better suit the needs of an S&T human capital model? By relating education and experience with earnings and productivity, human capital theory has contributed a great deal and it has proven itself a useful economic concept through empirical analyses time and again [60,61,62,63,64,65,66,67,68]. Yet, for our purposes, it sometimes comes up theoretically short. Its intuitive appeal and face validity have not yet been translated into operational and theoretical success, at least not within the realm of research evaluation [69].

4   Human Capital Theory and Research Evaluation

As a tool for research evaluation and sociology of science, human capital theory needs some fleshing out. Human capital theory generally assumes that there is no variation in its predominant proxy variable, educational attainment, among scientists [70]. S&T human capital must recognize variation in educational background: even no two physics degrees are the same, and having a Ph.D. does not trump all other educational attainment in our estimation, it merely adds to it. The formal human capital of scientists who received all of their degrees in one discipline is qualitatively different from scientists who obtained a liberal arts education, followed by master's work in biology, and a Ph.D. in biochemistry. In addition to curricular differences, scientists are not educated alike *pedagogically* and, thus, the tacit foundations of their understanding of science are not the same.

This tacit dimension of knowledge as articulated by Polanyi [9] is crucial to S&T human capital. "While tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence all knowledge is *either tacit or rooted in tacit knowledge*" ([10] p.19) [71]. We argue that tacit knowledge is tied to its broader context and becomes integral to S&T human capital [72]. S&T human capital must be prepared to articulate the many ways in which scientific careers are built tacitly and experientially. Because of the complexity of scientific jobs, it is critical to assess the content of the work that yields new experiences and competencies. For example, some scientists pursue postdoctoral training; some a mix of industrial, consulting, and

academic work experiences; and others, perhaps, international experiences. Moreover, a variety of activities only indirectly related to publication productivity nevertheless contribute to the work of scientists. For example, the ability to write successful grant proposals, manage complex funding streams, attract students and researchers, and participate in professional discourse are all elements of S&T human capital. Human capital is itself an output of S&T human capital both in the formal and experiential senses as well as in terms of scientist's role as teacher, collaborator, and mentor of students. Finally, human capital can be conceptualized as a dynamic element of scientific production, evolving in planned and unplanned ways that leave lasting imprints on science, institutions, and other researchers. Careers, even of scientists who do not remain in the sciences, have longevity: they are products constantly in the make and remake, and they are not forged in splendid isolation.

5   Social Networks and Social Capital Theory

Some of the earliest work recognizing the importance of the social network to science and scientists was performed by Derek de Solla Price [73] and Diana Crane [74,75] on the concept of invisible colleges of scientists—roughly what we call knowledge value collectives. Invisible colleges [73,74,75,76,77,78,79] are built on interpersonal relationships that facilitate various forms of collaboration [80] and communication among groups of scientists and permit them to exchange ideas and keep tabs on research within their own or adjacent fields. Invisible colleges depart conceptually from knowledge value collectives or other social network theories[81], in that they represent

the "in-group" or prestige or power group within the field—the very core that those on the outside seek to emulate and who are enormously productive [82,83]. The invisible colleges and the venues in which they operate—conferences, institutes, working groups, electronic communications—constitute both social inputs and outputs for individual scientists as well as science as a whole. This line of research recognizes that intellectual and scientific development occurs before, during, and after publication, and stresses that the all three are critical links in the knowledge chain [84,85,86,73].

Because of logistical complexities, empirical work on invisible colleges is rare, with few exceptions of note. Diana Crane [74,75] examined the communication patterns of rural sociologists in the diffusion of agricultural innovation. She traced direct and indirect ties in determining that a small group of productive scientists are directly interconnected with one another and attract an outer ring of less (or otherwise) productive scientists into indirect communication and influence. Mullins [87] concludes from his comparison of communication ties among scientists that disciplinary orientation has obvious importance, but that scientists often communicate informally with scientists from other fields as well. Crane [74], suggests such influences are cultivated by scientists who wish to maintain exposure to new ideas in other areas of science. She found that scientists, in identifying others that influence their work, are just as likely to select scientists outside their disciplinary borders as within.

What is most interesting about the social network [88] approach for our purposes no matter how it is cast, is that it places the productivity of individuals in relation to the productivity of the larger community of scientists working on similar problems. What scholars like Price and Crane did not explore, however, is the nature and functioning of

those links themselves. Best known for their consideration of this topic are Mark Granovetter [89] and Ronald Burt [90,91,92]. Granovetter was interested in explaining how people get jobs through social networks and observed that they more often got them through distant social relations than proximate. He argued that "weak ties" (e.g., friend of a friend) represent social resources not available through stronger ties (e.g., family). People who have strong ties tend to share mutual friends and professional contacts; people with weak ties tend not to. "Intuitively speaking, this means that whatever is to be diffused can reach a larger number of people, and traverse greater social distance when passed through weak ties rather than strong." ([89] p. 1366) [93].

In contrast, Burt [90,91,92] examines how entrepreneurial managers acting in communication networks within and between companies make use of their position within the structure to their own advantage. Similar to Granovetter, Burt argues that managers broker and bridge "structural holes" in communication networks thereby weeding out the redundancy of their information networks and making themselves indispensable to the organization. "The structural hole is an opportunity to broker the flow of information between people and control the form of projects that bring together people from opposite sides of the hole" ([92]).

It was not until the 1980s that scholars like Bourdieu [94,12,13] and Coleman [14,15] began referring to "social capital."[95] According to Bourdieu, "social capital is the sum of resources, actual or virtual, that accrue to an individual or group by virtue of possessing a durable network of more or less institutionalized relationships of mutual acquaintance and recognition" ([13] p. 119). Whereas human capital theory has been dominated by economic perspectives, social capital theory has its roots in the sociology

of community, neighborhood, and family [96,97]. As of yet, few studies have attempted to apply the concept to scientific research, some exceptions being Walker, Kogut, and Shan [98]; Gabbay and Zuckerman [99]; Nahapiet and Ghoshal [100]; [101]; and Dietz [102].

To Coleman [14,15], social capital is not a single entity but a variety of different social phenomena that possess some aspect of structural relations which facilitates actions of individuals or groups. Unlike human capital which resides within the brain of its owner, social capital "inheres" in relations between people and therefore cannot, itself, be owned[103]. It is in this public goods capacity that social capital governs human behavior through the exercise of individual obligations and expectations and community norms and sanctions [14,15,56,104,105].

For our purposes, we conceptualize social capital as the cooperative glue that binds collaborators together in knowledge exchange. Like all forms of capital, social capital must, first and foremost, be used in order to become useful. Second, it must exploit the complementary assets of scientists, mentors, students, administrators, and key community figures who work together toward an agreed upon and mutually beneficial end [106]. Third, value must be created through the appropriation of information into knowledge in whatever of its many formal and informal manifestations. Nahapiet and Ghoshal [100] and Tsai and Ghoshal [107] argue that social capital facilitates the development of "new forms of association and innovative organization. The concept, therefore, is central to our understanding of institutional dynamics, innovation, and value creation" ([100] p. 245).

Finally, Coleman's conception of the relationship between human and social capital serves as a critical building block of our model of S&T human capital. For Coleman [14,15,56], social capital acts to facilitate the exchange of human capital among people. A particularly strong proponent of public education, Coleman demonstrated that higher levels of social capital present in family and school settings was related to lower levels of school dropouts. Within the family, even if the parents possess large stocks of human capital, the child will not benefit if the social capital is absent [14,108,109,110]. We argue that the interplay between social and human capital is so fundamental, intimate, and dynamic that neither concept is fully meaningful by itself, making it nearly impossible in the end to pinpoint where one leaves off and the other one picks up.

6   S&T human Capital and the Qualities of Scientific Work

Let us summarize where these theories leave us. First, scientists do not exist in a social vacuum. They are members of various social institutions, and they are colleagues at a variety of levels. It does not make sense to separate individual scientists from their individual abilities, time-in-career, and interdependence with others. We must apply the dynamic tension between human and social capital in understanding how both continue to develop over the life of a scientist, the life of work groups, the life of fields, and maybe even the progress of science.

The evaluation of science requires an approach in touch with knowledge of the social context of scientific work. An S&T human capital model is first a model of scientific work and its social qualities (e.g., Bozeman and Rogers [11,37,38,39]); the

evaluation methodology flows from this more fundamental conceptualization.   Much of this capital, especially that aspect that is interpersonal and social, is embedded in social and professional networks, technological communities [111,112], or knowledge value collectives.   These networks integrate and shape scientific work, providing knowledge of scientists' and engineers' work activity, helping with job opportunities and job mobility, and providing indications about possible applications for scientific and technical work products.   Since the production of scientific knowledge is by definition social, many of the skills are more social or political than cognitive.   An increasingly important aspect of S&T human capital is knowledge of the workings of the funding institutions that may provide resources for one's work.

Let us emphasize that none of this discounts the more traditional aspects of individual scientists' talents, such as the ability to conduct computer simulations of geological fracture patterns or the ability to draw from knowledge of surface chemistry to predict chemical reactions in new ceramic materials.   Our concept simply recognizes that in modern science being scientifically brilliant is only necessary, not sufficient.   In most fields, a brilliant scientist who cannot recruit, work with, or communicate with colleagues or who cannot attract resources or manage them once obtained, is not a heroic figure but a tenure casualty or one or another variety of underachiever.   Moreover, even in the more focussed concern of traditional human capital—pay levels as surrogates for performance—we argue that this broader concept is useful.   While the variance in income among Ph.D. holders is less than for the general population, much variance remains to be explained and formal credentials (since there are usually none beyond the Ph.D.) and additional formal education cannot provide much help in the explanation.

Our S&T human capital model assumes:

- Science, technology, innovation, and the commercial and social value produced by these activities depends upon the conjoining of equipment, material resources (including funding), organizational and institutional arrangements for work and the unique S&T human capital embodied in individuals.

- While the production function of groups is not purely an additive function of the S&T human capital and attendant non-unique elements (e.g., equipment), it resembles closely an additive function. (The "missing ingredient" in such aggregation is the quality of the fit of the elements to the production objectives at hand.)

- At any level (see below), from the individual scientist to the discipline, field or network, the key focus is on capacity and capabilities. What factors enhance capacity, diminish it or simply change the reservoir of capabilities inherent in individuals and groups?

7 S&T Human Capital as a Multi-Stage Model

Perhaps the best approach to fleshing out a S&T human capital model for research evaluation is to develop schematics for analysis. At the *individual* S&T human capital level, the model includes the endowments (human capital) of the individual researcher (cognitive, knowledge-based, skills-based) and the researcher's social ties, both direct and indirect (i.e., social capital). At the *project* S&T human capital level, the focus is on the aggregate of all project participants' endowments and social ties, as well as the physical

and economic resources available to a project. Beyond the project and program levels, one may consider S&T human capital in virtually any social aggregation including field, subfield, informal network or discipline. We focus on the knowledge value collective level because of its particular relationship to questions of capacity [11,37,38,39]. Each level of analysis is dynamic and functions in response to a set of distinctive drivers and events. Research evaluation may focus on either level, examining the capacity (i.e., S&T human capital + physical and economic resources) of the individual, the project (or a similar organizational unit), and the higher levels of social organization (e.g. knowledge value collective, network, scientific field).

Regardless of the level of analysis, one assumes constantly changing S&T human capital indices. In the case of the individual, new ties emerge, new skills develop, but there are also decrements in skills and ties as one moves into different fields and abandons earlier career work. In the case of the project, similar changes occur with new and reformed combinations of project (or organizational unit) members and new levels and types of physical and economic resources. Most important—and most difficult to analyze—entire fields, disciplines, and knowledge value collectives can be said to be constantly changing with respect to their capacity, defined in terms of (1) available economic and physical resources, (2) aggregate S&T human capital, (3) the complementarity of S&T human capital, and (4) the patterns of deployment of resources, including S&T human capital. We expand on these assumptions in the remainder of the paper, focusing on the individual- and project-level only (we treat the knowledge value collective level in other papers [11,37,38,39].

8   S&T human capital: The Individual

Figure One provides a model of the individual's S&T human capital, showing, within the "box" (i.e., the individual researcher) unspecified dimensions of cognitive skills, scientific and technical substantive knowledge, and work-related or craft skills.

8.1   S&T Internal Resources

Let us begin by considering the "internal resources" of the scientist or technologist. To represent those internal resources we have assumed that any individual's scientific capabilities can be classified into one or more of three presumably overlapping internal resources categories:

1. *cognitive skills*

2. *substantive scientific and technical knowledge*

3. *contextual skills.*

The exact ways in which these capabilities relate to one another is, to us, an open empirical question, though studies in the psychology of science have begun to point the way (e.g., Prpic [113], Simonton [114,115]. We are less concerned with the detailed specification of these internal resources than with their recognition as a component of S&T human capital. Nevertheless, we can provide a succinct description of each. By "cognitive skills" we refer to the those cognitive abilities (such as mathematical reasoning, memory, ability to synthesize) that are largely independent of context or, more likely, interact with context but are not determined by context. The abilities in the cognitive skills category pertain to science but not exclusively to science. "Substantive

scientific and technical knowledge" is best described as the type of knowledge one obtains through formal scientific education and reading-knowledge of particular theories and explanations, specific experimental and research findings. Finally, the category "context skills" refers to knowledge gained by doing and creating and includes tacit knowledge, craft skills, and knowledge specific the design and implementation of specific research or experimentation plans (such as, for example, building of single-purpose equipment configurations). It is important to emphasize that context skills are not less valuable because of their specificity [116]. Context skills cannot, by definition, be directly brought to new scientific and technical problems, but they provide the basis for problem solving heuristics and comprise an action repertoire that is transferable to other contexts.

We assume that each of these three overlapping categories of internal resources has n dimensions (varying according to the individual) and that each individual can be said to have a "loading" on each dimension (possessing more or less of the ability associated with that dimension). Some individuals, generalists, tend to have many more dimensions, with lower level loadings; others, specialists, tend to have few dimensions and load high on at least some of them. Similarly, there is an expectation of imbalance among the categories. Thus, some individuals will typically have more capacity (i.e., more dimensions and higher loadings) in formal knowledge while others will have more capacity in context-specific knowledge. These levels of capacity typically relate to career trajectories, such that individuals tend to possess proportionately more formal substantive knowledge at the beginning of the scientific career and increasing, over time, their

context knowledge (and perhaps in many cases substituting it for diminishing formal knowledge [see Groot [117] on depreciation of human capital]).

It is important to note that the capabilities we refer to as internal resources are not completely coincident with human capital. Typically, human capital focuses on formal educational endowments (see Griliches [118]) for an overview of recent research) and pays little or no attention to contextual skills and not much more to cognitive skill, even ones subject to enhancement through training.

8.2   S&T Social Capital

Figure One depicts not only the internal resources of the scientist but also those external resources directly relevant to the production of knowledge and technology—social capital and embedded network ties. The different shapes of nodes implies the convenience of recognizing qualitatively different types of linkages. Those differences may be based on the institutional setting of the network partner (e.g., industrial, academic) or the role (e.g., entrepreneur, funding agent, scientific colleague). While we are less concerned at this point with the strength of ties or the density of networks, research on scientists and technologists and their networks (e.g., Meyer-Krahmer [119]; Pickering and King [120]; Constant, Sproull, and Kiesler [93]; Beckmann [121]; Liberman and Wolf [122]; Liebeskind, et al., [123]) shows that these and other structural features of the network may predict network members' behavior and, presumably, the accumulation of S&T human capital. Our point is a simple one: scientists employ a wide variety of network-mediated resources to enable their work [124] and these resources—this scientific, technical and commercial social capital—is uniquely configured for any particular

scientist.   As   such, it is part of the unique S&T human capital he or she brings to any project or work task.

In Figure One, the broken line and shaded area represents the intersection of the research project with the individual's S&T social capital (network ties) and internal resources.   Our focus is on evaluation of research projects and, thus, our social organization compass points toward the ways in which the individual's S&T human capital tracks against the project's boundaries.   But any social configuration can be mapped against the individual's S&T human capital resources to depict their deployment. A similar map could be drawn for a research program, a single research study, a laboratory or virtually any social organization or set of social interactions.

8.3   Individual S&T Human Capital and Life Cycles

An important aspect of the S&T human capital approach to evaluation is recognition of the evolution of the scientist throughout his or her productive life cycle.   Figure Two represents a part of the individual scientist's productive life cycle, focusing specifically on a scientific project as a time anchor.

S&T human capital is constantly changing.   Depending on the individual, there may be more or fewer dimensions of each at any particular point in time and the individual may "load" at a different level on the dimension at any particular point in time. Thus, at time *t* the individual may have three dimensions of context skills which, for example, might include the ability to operate a combustion chamber, the ability to interpret simulations programs, and the ability to insulate burners.   At time *t+1* those

skills may be enhanced or diminished or lost; new skills may be added at a particular level of capability. Similarly, at any particular time, we can identify social ties, direct and indirect ties with scientific and technical academic colleagues, but also ties relevant to the use of scientific and technical knowledge from industrial settings.

In Figure Two, at time *t-1* (pre-project) the individual, at least in this example, has fewer network ties and fewer dimensions of knowledge, skills, and craft. But in time *t+1* the individual has more dimensions of knowledge, skills, and craft, and a greater number of social ties. In this case, the task for the evaluator would be to determine the relationship between shifts in S&T human capital and participation in the project.

The "evaluation problem" at the individual level is to determine the extent to which the project or program has enhanced the S&T human capital of participants. As a result of the project, are the participants better able to contribute to future scientific and technical endeavors? Has their S&T human capital increased, has it increased in ways for which there is likely a future demand, and has it increased *because* of participation in the project or program? The latter issue is methodologically most troublesome. Since, as we have already discussed, the individual's S&T human capital is virtually in a constant state of flux, isolating the influence of projects and programs cannot be done, at least in most instances, with great precision. But the problem is not qualitatively different from determining the impact of a project on the creation of any other output (such as a technological device, a research publication, or new jobs). Indeed, determining the impact of a project on the individual's S&T human capital will likely involve fewer assumptions and a somewhat less complex model. More troublesome is determining the utility of S&T human capital endowments on future work since it is impossible to know

the skills needed for technological advance apart from a knowledge of the advances themselves. Once again, however, the task is not qualitatively different from tasks already undertaken. Human resources planning in science and engineering is done routinely, albeit through a glass darkly. An S&T human capital model renders the glass no darker and, perhaps, by focusing on a wider array of capacity variables, may even let in a bit more light to the forecasting task.

9 S&T Human Capital at the Project Level

Figure Three depicts the resources employed for two projects by the entire project team. A realistic map would, of course, be infinitely more complicated, but at least this schematic provides the fundamental idea. Project teams can be viewed as the amalgamation and "fit" of the S&T human capital assets of all project members.

One important implication of the S&T human capital model is its implications for management. At the individual level, the management task is to properly assess the individual's S&T human capital and then to ensure that it is deployed in a way that maximizes the project's (organization's, program's) goals. Thus, the internal resource dimensions must be tapped and social resources must be exploited effectively. A beginning point, then, is a good knowledge of the individual's unique resources as represented in the S&T human capital model. Then more "generic" management activities become important—providing incentives, aligning individual and project goals, providing funds, equipment and other resources needed to fully exploit S&T human capital.

At the project (or any group) level, the management task is chiefly one of fitting together S&T human capital assets of unique individuals. Once one moves beyond the individual level, the degree of fit in knowledge, skills, and craft becomes vital. To what extent does the internal resource profile of one project member complement that of others? Similarly, the S&T social capital aspects of the project become much more complicated. In the first place, there is likely to be some overlap in network ties such that (in this respect only) the whole may be less than the sum of its parts. Second, the command and allocation of resources becomes a major issue once one focuses on the project level and, generally, the management structure (formal and informal) takes its place alongside S&T human capital issues. Thus, an S&T human capital-based evaluation of a project implies a focus on the increment of S&T human capital (both with respect to the individual members of the projects and their role in networks or scientific specialties), but the determinants of S&T human capital changes are not easily modeled, flowing as they do, not only from project resources and their deployment but from a series of complicated precursors which determine *ex ante* S&T human capital. For example, studies (e.g., McGinnis [125]) in the sociology of science have shown that the productivity of postdoctoral research positions are contingent on a variety of precursor issues including the social capital the postdoc brings to the new position.

10   Scientific and Technical Human Capital Evaluation: Data Sources and Measurement Issues

We have not as yet applied a S&T human capital model to actual data accumulated (though application is underway). Nonetheless, we have a considerable body of empirical work that led us to the conclusion that an S&T human capital model is required. Having recently conducted extensive case studies [25,26] of more than 20 public-sponsored basic research projects we have developed some ideas about data requirements.

These diverse case studies, some set in universities, some in federal laboratories, some involving large teams of scientists, some just a couple, showed us how much is missed by focussing on "the products" or even on sharp boundaries of projects. For example, one of case studies [23] showed us that the course of molecular biology has been strongly influenced by two spouses interacting over a career collaboration that began with intellectual discussions and romance in Parisian Left Bank cafes. In another case, breakthroughs in superconducting materials are best accounted for by the ongoing relations between a team of multidisciplinary scientists held together by an entrepreneurial science manager. The development of management, political, and network-based skills in the project were just as important to its outcome as the educational or cognitive endowments of the parties involved. In still another case, one involving development of state-of-the-art software, a work group's productivity could only be understood in terms of the entry/exit patterns of laboratory personnel and the specific talents gained and lost. None of these projects' secrets could be revealed via traditional benefit-cost analysis, product metrics, or cost-accounting. Each requires an

approach to evaluation that (1) is longitudinal, (2) examines networks or some other conceptual apparatus implying social connection, and is (3) capacity-oriented rather than product-oriented.

Having outlined a S&T human capital model for evaluation, let us consider more systematically the ways in which it differs from related models. Table One contrasts two models of evaluation and two models for the study of science. One may infer from this table that the evaluation methods flowing from an S&T human capital model are not radically different from other approaches but their implications are.

In applying an S&T human capital approach to evaluation, useful data sources can come from a variety of places. For example, those wishing to understand the development of S&T human capital can examine contracts and the ties they enable [126] or structured activity diaries [127]. But students of S&T human capital can use one important and fertile data source not typically used in traditional human and social capital studies: the scientist's curriculum vitae or resume. The CV is a reasonably standard means of recording career guideposts and accomplishments. It provides an excellent source of information pertinent to career trajectories and, when accompanied by probing questionnaires or interviews, can give an account of both the "what" questions and "why" questions as well. Most important, the CV is readily available. Many scientists provide them online in web pages but even if not already publicly available, scientists customarily provide their ready-to-distribute CVs without any "tailoring" or additional burden beyond putting them in an envelope or an email attachment. Nor is their much need for tailoring in most cases. The information in a CV is exactly what one would wish in an analysis of S&T human capital and scientific careers. It may not be utterly complete. For example,

it typically says little about the acquisition of tacit knowledge or about particular interactions with commercial users. But it almost always is a good starting point for gathering information about how the scientist has developed S&T human capital. It also provides some information relevant to network analysis by giving a list of collaborators and student advisees.

The CV is only a starting point. To measure capacity in projects, groups, networks, and knowledge value collectives, one must examine ties. These are revealed to a limited extent though the unobtrusive measures of citation and patent analysis but many vitally important ties are not reflected in formally discernible collaboration patterns. Thus, interviews and questionnaires are likely an indispensable aspect of S&T human capital evaluation.

The S&T human capital approach is inherently longitudinal and focuses on longer-term changes in capacity. In some cases it is even amenable to retrospective analysis (e.g., by examining the guideposts provided in curriculum vitae). If one takes an event history perspective on S&T human capital, one is drawn to the critical events that shape the productivity of individuals and groups over lifetimes.

11   Conclusions

The complexities of an S&T human capital approach to evaluation are prodigious because the approach is holistic. Rather than focusing on discrete products produced by projects, the focus is on the capacities generated by projects which, in turn, require knowledge of the full complement of human resources brought into the project and some

idea as to the determinants of those resources. This capacity can either be appreciated on its own grounds or it can be interpreted as a set of scientific and technical footprints that say more, not only about knowledge value than would traditional monetary valuation of outputs, but of science policy investment-value than would state-of-the-art valuation or any other of the host of traditional approaches. This is inherently a more difficult task than enumerating discrete products or even counting the market value (or shadow prices) of discrete products.   Thus, given the difficulties of the S&T human capital model for evaluation, why pursue it?

The S&T human capital model for evaluation seems to have at least four advantages: (1) it deals with the life cycle dynamics and the evolution of scientific and technical fields, (2) it conforms more closely to scientists own conceptions of their work and exploits knowledge developed in the social study of science, (3) it can act as a counterweight against policymakers' needs to "rush to judgment," (4) it provides an alternative based on something other than monetized value of science.

R&D evaluations using other models and assumptions rarely enter into consideration the dynamism of scientific careers and scientific and technical networks. The S&T human capital model inexorably draws attention to the change dynamics of individual scientists and technologists and the social organizations in which the work is performed. Other approaches, including those based on microeconomic theories of value, pay little or no attention to "the long run" or to change dynamics except as they pertain to estimating streams of economic benefit over time.

A second advantage of the S&T human capital model of evaluation is that it conforms to scientists' and engineers' concepts of their work, at least as described in

social studies of science. With the possible exception of some industry-based R&D projects, scientists do not see their careers in terms of particular products developed for particular purposes but more often view their work as relatively seamless and interconnected. Those interconnections rarely track well against specific formal projects and programs. Indeed, our own studies [25,26] show that researchers often cannot partition their work according to project or funding agent.

A third advantage is that the S&T human capital model provides an alternative to evaluation approaches that require monetized value. While it is certainly appropriate to estimate the returns from research in economic terms, everyone involved in research and research evaluation readily accepts the limitations of assessments based exclusively on narrow conceptions of economic value. An approach based on analysis of capabilities can, of course, present new possibilities for assessing economic value [128], but clearly a S&T human capital model can stand on its own.

Finally, there is a practical political advantage to a S&T human capital model—it provides an approach that cannot possibly be static and cannot ignore the time requirements of projects and programs. Policymakers have pressures for quick results but often recognize the difficulties of applying a "what-have-you-done-for-me-lately" approach to evaluating science. By pursing an S&T human capital model, perhaps as a companion to a more conventional approach, policymakers have an alternative to quick results—demonstrable improvements in capacity.

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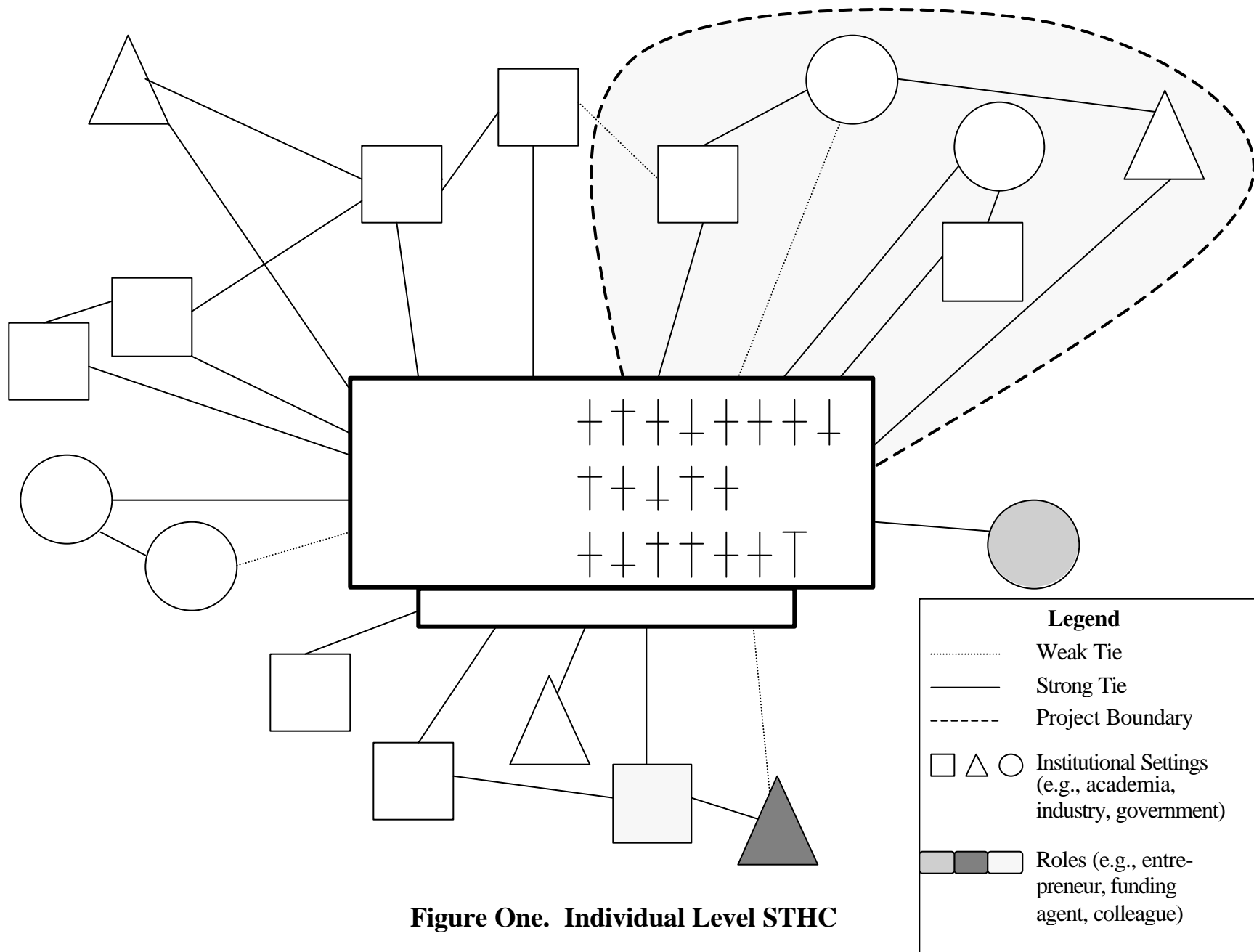
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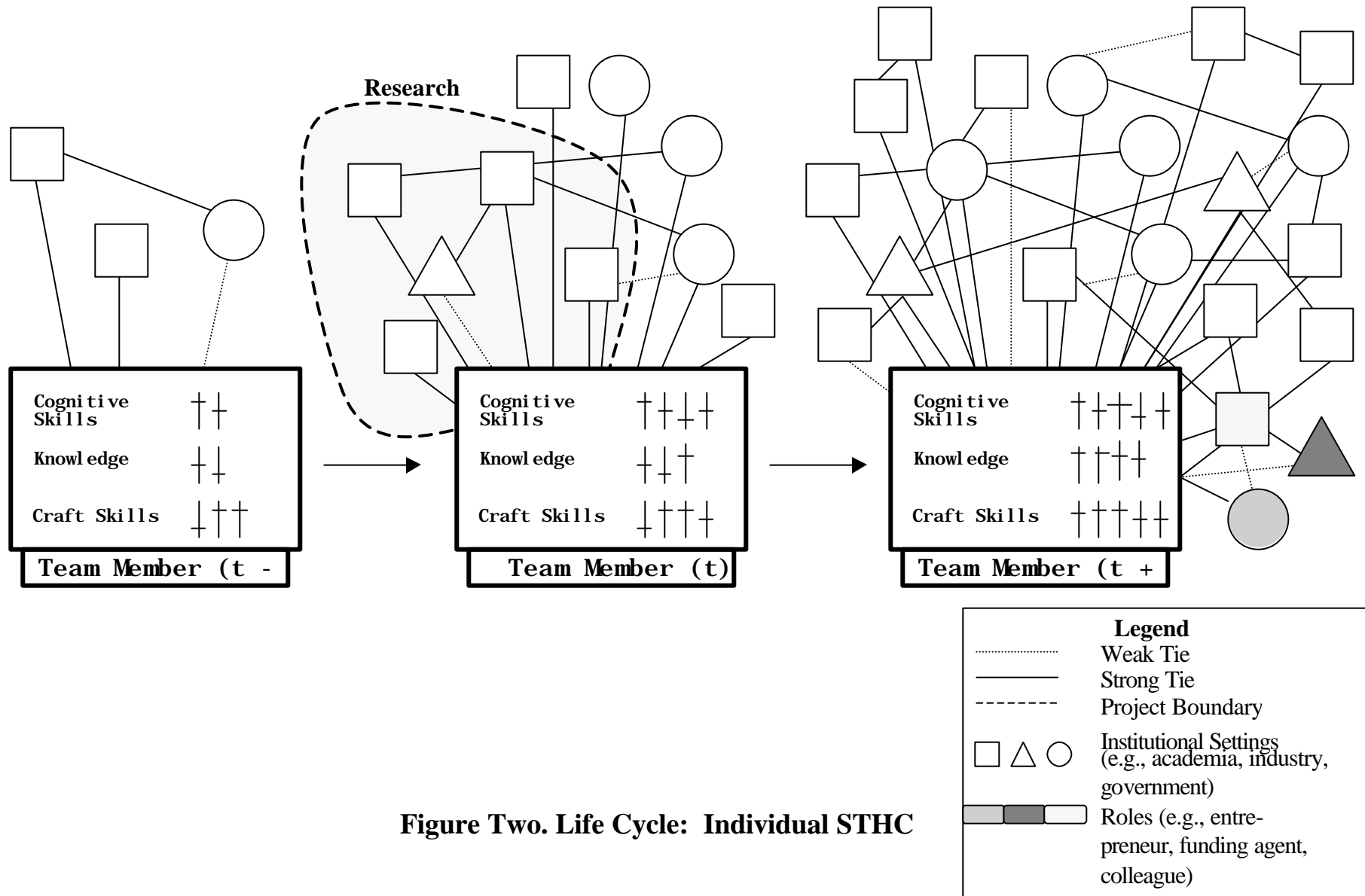
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Table One. Contrasting Models for Analysis of Scientific Productivity

Character-istics of Model	**Individualistic: Human Capital**	**Individualistic: Output Evaluation**	**Social: Network Analysis of Scientists**	**Social: S&T human capital**
Focal Dependent Variables	Income or status as derived from formal education and training	Scientific outputs such as publications, patents, algorithms	Citations, communication interactions	Productivity of (groups, collectives and networks) in terms of ability to produce knowledge and new applications of knowledge
Preferred Analytical Techniques	Econometrics /production function (e.g. Cobb-Douglas)	Varied, including benefit-cost analysis, case studies, citations	Sociometrics, citation analysis	Multiple, including sociometrics, citation analysis, supplemented by case studies and life course studies
Illustrative Studies	Becker	Kingsley, Bozeman and Coker (1995)	Crane (1969); Allen (1977)	See Bozeman and Rogers, 1998
Chief Limitations	Limited applicability to post-Ph.D. scientists; income as productivity measure	De-emphasizes social fluidity of science, longitudinal component difficult to account for	Limited utility for policy evaluation, minimal institutional components, normative criteria often unclear	Costly; difficult to identify boundary rules
Chief Advantages	Precision, formalization	Conforms to policymakers' and managers' evaluation expectations	Provides good explanations of the social dynamics of science	Useful for capacity-oriented analysis, conforms to contemporary social milieu of science, enables longitudinal analysis

Figure One. Individual Level STHC

Legend

············ Weak Tie

———— Strong Tie

- - - - Project Boundary

□ △ ○ Institutional Settings (e.g., academia, industry, government)

Roles (e.g., entre-preneur, funding agent, colleague)

Figure Two. Life Cycle: Individual STHC

Cognitive Skills

Knowledge

Craft Skills

Team Member (t -

Research

Cognitive Skills

Knowledge

Craft Skills

Team Member (t)

Cognitive Skills

Knowledge

Craft Skills

Team Member (t +

Legend

Weak Tie

Strong Tie

Project Boundary

Institutional Settings (e.g., academia, industry, government)

Roles (e.g., entrepreneur, funding agent, colleague)

Figure 3. Project Level STHC