From the Triple Helix to a Quadruple Helix ?

The Case of Dip-Pen Nanolithography.

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Introduction

In this article we argue that transformations in the cognitive, economic, organisational and cultural environment of many industrially advanced countries are such that in addition to the three erstwhile strands of university, enterprise and government constitutive of the Triple Helix, it may prove enlightening to extend and enrich Leydesdorff's and Etzkowitz's model through the introduction of a fourth strand, namely society.

The fourth societal strand of the helix may intertwine government with enterprise where government establishes technical programs intended to promote industrial competitiveness, and in so doing, fabricates and publicises society broad promises that generate public expectations. Such promises subsequently set the stage for a profitable market for enterprise because of the introduction of fresh social demands. On another register, the introduction of the societal strand may prompt university scientists to apen to their research programs historical or cultural images or language that place their investigations into a larger context which provides a bridge between research findings and ideas for broader cultural projects and eventually products. Of course, questions of societal concerns such as climate change, health or the environment, may likewise constitute an important impulse for the inclusion of society into the Triple Helix relationship.

The importance of any specific strand in the innovation process and its conjunction with other strands is determined by the content, intensity, direction and the alliances of the actors belonging to the different strands. On a quite different register, it should be noted that in some instances actors exhibit multiple expectations which link the rationale of several strands, or alternatively, an actor may exhibit expectations that do not properly fit the norms of his strand. The latter scenario demonstrates that through such a mis-match the unit of "strand" may not always offer the most opportune unit of analysis. This theme of units of analysis will be introduced again in the conclusion of this article.

In the pages that follow we will explore the dynamics of a Quadruple Helix in the case of Dip-Pen nanolithography and the enterprise that developed and commercialised the novel technique _NanoInk Incorporated. Dip-Pen nanolithography is a technique for depositing nanometric organic and inorganic particles, often self-assembled monolayers molecules, on a selected substrate, in a highly precise and controlled pattern in order to perform definite tasks such as creating arrays for biological purposes, encoding informations or introducing precise shapes.

Different configurations of the Quadruple Helix arose during the development of the Dip-Pen _ the initial research phase, the company start-up phase, the enterprise development phase, and the "nanofication" phase.

Nanofication refers to diffusion on a societal scale of training in nanotechnology for use and for the preparation of technical personnel; it also concerns a general society wide familiarity with things nano.
The initial phase of the trajectory of the Dip-Pen nanolithography device was dominated by the university strand. Government figured here as an ambient, recessive force that promoted scientific and technical research in areas related to nanoscale science and technology _ in response to technical difficulties encountered by the US electronics industry. Society constituted a subtle yet decisive strand as it provided inspiration for the emergence of the concept of writing that significantly underpinned much of the investigation behind the research instrument generated during this opening period. This vision of writing in terms of pen, parchment and ink would become a key theme in the final episode of our case study that is dominated by the societal strand and where the commercial product and cultural projects are synonymous with nanofication.
In a second phase during which the nanolithography company NanoInk Incorporated was created, the university strand remained dominant even though the organisational objective was entrepreneurial. During the start-up period, expectation of matters entrepreneurial straddled academia and the firm. This demonstrates that intentionality oriented in a certain direction is not necessarily synonymous with the specific organisational base. At this time, the task consisted of transforming a promising but very fickle research instrument into a reliable economic tool. At this stage, merchandising of a technically high performing nanolithographic device was not the issue. Here the relationships between university strand and the enterprise strands vehicled the same general expectation of developing a practical routine tool - one for commercial purposes, the other for research purposes. Research teams cooperated in this pursuit, the societal and government strands remained largely absent.
In a third phase when the mature firm emerged and began production and sales of the Dip-Pen nanolithography tools, research was largely conducted inside the enterprise or was selectively co-sponsored by the firm and users who had introduced novel adaptations in the course of their local application of nanolithography. The thrust of NanoInk Inc. was oriented to the identification of potential markets, to product line development, and to sales. The company introduced five divisions which included manufacturing nanolithographic coding, nanobiology, nanostemcells, and nanotechnology oriented to education. Company logic largely addressed public and private scientific research, with growing attention to non-research commercial applications. We see here a conjunction of the entrepreneurial and societal strands where the entrepreneurial strand is foremost.
The final phase, nanofication[1], is largely dominated by the societal strand in combination with the enterprise strand. Government is present to the extent that it continues to circulate information concerning the promises of nanotechnology in the form of medicine, new materials, energy and so forth, and announcing the future link between economic prosperity and an explosion in the number of nano-related employment possibilities and the centrality of nano enterprise to the future of America.
NanoInk Inc. invented a new line of nanowriting devices to be used in high schools and colleges to teach the younger generation how nanotechnology operates, to familiarise it with principles of nanotechnology and to inculcate the broader public with a nanovision. It is interesting to note that universities figure here as consumers

[1] During the fourth stage, numerous other initiatives were taken which will not be presented in this text. For further informations on these developments see the article by A.Marcovich and T.Shinn "Instrument Research, Tools and the Knowledge Enterprise 1999-2009 Birth and Development of Dip-Pen Nanolithography " (to appear in *Science, Technology and Human Values* 2011)

of a message which they have in part initiated. Of utmost importance, specialised nanotechnology pedagogical journals have now emerged and specialised nanoinstruction has penetrated education.

Note that the societal strand is present in some capacity in all the four phases, and predominant in at least two of them. From this, it is reasonable to judge that the inclusion of a societal strand in the Triple Helix enriches it through introducing an additional observational and explanatory parameter.

In this article we shall examine each of these four phases indicating which strands and combinations of strands are paramount and precisely why; the concept of expectations will serve as an underlying theme throughout.

An outstanding advantage attached to the analysis of the innovation processes in terms of temporality is that it invites us to study Triple Helix or in our case Quadruple Helix parameters in terms of strand permutations. These permutations introduce the possibility of the inclusion of previously unnoticed strands and equally important the pairing of strands which has complex consequences. The dynamics of binomes strands will be analysed in the conclusion of this article where we will use the concept of Niklas Luhmann for their exploration.

1. Initiating the Dip-Pen nanolithography device -instrument research.

Three of the four material and intellectual preconditions for the invention of Dip-Pen nanolithography pertained strictly to academic research and uniquely belong to the university strand of the helix. A fourth essential precondition , which takes the form of a historically based cultural analogy, belongs to the society strand. Government constitutes a remote back drop and enterprise is conspicuously absent. The three university items include the Atomic Force Microscope (AFM), Self-Assembled Monolayers (SAMs), and the understanding that nanometric objects such as molecules behave deterministically and are susceptible to precise control.

Government support for the kind of instrument research that emerged in connection with the AFM and with SAMs and which was increasingly linked to the perception of molecular determinism was well in place as early as the 1960's. This is nowhere more evident than in the public funding provided for US electronics research and industrial programs, and for solid state physics and semi-conductor research[2]. Investigations that led to the instrumentation nanoscience research revolution, which spawned the Scanning Tunnelling Microscope and AFM, and that stimulated materials research in the form of epitaxy and the development of SAMs, were expressions of active government backing relevant to the birth of Dip-Pen nanolithography during the 1990's. In this period, american science policy circles grew increasingly worried by a technological competition from outside the country and strove energetically to develop a new policy that would direct huge resources into research on the nanoscale. In the year 2000 this gave rise to the US Nanotechnology Initiative (NNI). The work of Mirkin was affected by government orientation and the availability of public largess. It is no accident that Mirkin's big Chicago laboratory was the first federally financed nanoscale research institute in America. Here the government strand constitutes a favorable environment where the academic and distinctly societal strands could flourish.

Nanolithography as generated through the technique of Dip-Pen instrumentation was developed in late 1998 and made public in an article by Chad Mirkin and his team titled "Dip-Pen Nanolithography" appearing in the

[2] P.Forman "Behind quantum electronics: National security as basis for physical research in the United States, 1940-1960," *Historical Studies in the Physical and Biological Sciences*, Vol. 18, Pt. 1, 1987, pp 149-229.

prestigious journal *Science* in January 1999[3]. Chad Mirkin is professor of Chemistry, Medicine, Materials Science and Engineering at Northwestern University, and director of the International Institute for Nanotechnology and the Center for Nanofabrication and Molecular Self-Assembly. Today he serves as science advisor to president Obama.. At the time this article appeared, nanoscale lithography already enjoyed some interest among nanoscale researchers. There existed a variety of nanolithography techniques, including direct contact elastomer stamping, electro-beam lithography, and etching. Originally, when Mirkin's group began work on the project, the aim was not to develop a nanolithographic instrument. The topic at hand was narrowly instrument research. As Mirkin and his group recount in their January 1999 article the inspiration behind the Dip-Pen, was first explicitly the solution to a technical problem (the formation of a water droplet on the AFM tip at ambient temperature) that hindered the resolving power of the atomic force microscope (AFM). In fact, the problem of the water droplet soon became transformed from a research instrument obstacle into one of the alleged fundamental resources of the DIP-PEN lithography tool _ thereby ink like compounds are transported molecule by molecule from the tip of the AFM to a substrate, in the same way that ink is transferred from a pen to paper. In effect, this redefined AFM device became a writing tool at the nanoscale.

In its early development, the Dip-Pen deposited dots having a separation of approximately five nanometers which contrasted with the one hundred to two hundred plus nanometers separation characteristic of other existing nanolithographic technologies[4]. Mirkin's article has drawn much attention inside the scientific community and beyond. The technical discovery constituted the foundation of a new nanolithographic instrument and subsequently its transformation into a commercial tool. A secondary AFM tip was used to monitor, decode, or to ascertain the properties of the deposited nanoscale droplets.

Despite its promise to produce complexity, early DIP-PEN instruments nevertheless remained relatively simple consisting of just a few individually operating pens and only two categories of materials were deposited on a very small number of substrates.[5]

From the very outset Mirkin's culturally and historically inspired perception of his novel research instrument as a writing and reading device explicitly propelled the social strand to the center of his efforts and the center of the dip-pen trajectory. In his inaugural article, Mirkin introduced a foot-note where he referred to the place of writing in the history of mankind and anchored his instrument in this tradition, which he describes in terms of pen, parchment and ink. Significantly, Mirkin constantly mobilise this cultural metaphor in later efforts, as can be seen in the language of several patents that he took out on the Dip-Pen device. This language based vision of a societal expression of his innovation would subsequently assume a concrete form when it became the basis of a commercial project, and when it implicitly came to underwrite the nanofication program a few years later.

2. Starting-up NanoInk Incorporated _ development of a commercial tool.

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[3] Richard D. Piner, Jin Zhu, Feng Xu, Seunghun Hong, Chad A. Mirkin « Dip-Pen" Nanolithography *Science* 29 January 1999: Vol. 283. no. 5402, pp. 661 - 663

[4] For example the Molecular Printer of Nanoscience of BioForce Nanoscience Prints spots and lines from 1 to 60 microns, 100msec printing cycle, 20 nm stage resolution, 50 mm XY travel, multiplexing ability. http://www.bioforcenano.com/index.php?id=288 (consulted: 20/04/2010)

[5] While the Dip-Pen proper was at this phase characterized by relative simplicity, the AFM on which it depends itself constitutes a highly complex device, because of its electronic and computational environment.

Between the 2001 creation of the company NanoInk Incorporated and the 2005 full commercialisation phase, events were dominated by the transformation of the aforementioned research instrument into a robust and reliable efficient and standardised tool. A reciprocal interlaced balance between the university and enterprise strands characterise these crucial years. Progress in the venture required active and associated yet sometimes separate research by both strands, where the expectations to generate a robust tool were foremost for both sides but for very different motives _ fundamental research for the university and development of a commercial device for enterprise. As signalled above, during the initiating instrument research phase, the AFM, SAMs and control based on the operation of determinism at the nanoscale characterised the university strand; and the vision of pen, parchment and ink and its cultural and technological extensions underpinned the societal strand. By contrast, during this second pivotal phase, endeavours in high precision mechanics and computer-based control, both associated with high performance tools and configuration of manufactured apparatus, stood foremost. High precision mechanics and informatics of this sort are intimately tied to the enterprise strand. We once again see that two strands (university and enterprise in this instance) figure dominantly, while two other strands in the Quadruple Helix remain marginal.

Tool research and its concretisation in the form of the manufacture and commercialised products often in the form of kits, constitutes one of the "raison d'être" of NanoInk Inc. While Mirkin's team and other academic laboratories were capable of designing, constructing, improving, and using the device, the difference with NanoInk is that it strives to produce an apparatus sufficiently robust that can readily be used for problem solving and manufacture. The project of creating NanoInk Inc. germinated in the course of a 2001 Gordon Conference encounter between the well established high-tech entrepreneur always on the look out to transform a research instrument into a commercial tool, Chris Anzalone and Chad Mirkin who had just presented a talk on his state of the art Dip-Pen nanolithography device.

In 2001 Mirkin's instrument was technically capable of encoding and decoding complex data. For the entrepreneur Anzalone, the DIP-PEN was novel. In view of the demand for large scale and complex array production in science and industry, the potential for such a tool was high. At that date, Mirkin claimed that his proto DIP-PEN was already capable of depositing one million molecular nano-dots in the space where conventional lithographic techniques placed a single dot. Nevertheless Mirkin admitedly only had in hand an 8-pen device, but he was in the process of preparing a 32-pen apparatus. The research instrument was limited to "series writing" which meant that it was restricted to inscribing a single line at a time as opposed to multiple simultaneously inscribed patterns. Despite these limitations, Mirkin's instrument research exhibited promise. However, in order to concretise its potential, it would be necessary to transform the instrumentation research into a working tool. This constitutes an often complex dynamic that requires many fresh technological innovations and a mobilisation of many different categories of actors and organisations.

Anzalone and Mirkin decided to set-up NanoInk Inc, and Anzalone believed the first and largest market would be in the sphere of biology and bio-related applications

This transition phase between research instrumentation and tool, represents a period of intense interactions and multiform circulation of people, skills, materials and information, within and between the academic strands and the enterprise strand of the proposed Quadruple Helix. This circulation is widespread, allowing scientists, students, engineers and technicians, brief informal visits to academic laboratories or enterprises, long-term exchanges, and professional relocation in alternative institutions. This dynamic is fuelled by demands from individuals based in one site or institution who require cooperation from individuals in other sites, which in turn may lead to a reformulation of the problem, the development of a novel tool, and once again travel to an alternative group and site.

Instances of this circulation are typified in the following episode. In August 2002, NanoInk engineers decided to use silicon nitride pens in order to make them tougher and more flexible than those employed by Mirkin, and this was obtained through a collaboration with the Quate AFM[6] instrument research group at Stanford University which resulted in two fundamental patents.

The evolution of the Dip-pen tool depends centrally on multiplication in the number of pens and in their coordination and alignment. This technology permits rapid production of an array with complex shape and a large number of patterned drops.

In 2000, eight cantilevers and tips were involved in array production. In 2004 the number had risen to 55 000 tips.

The variety of substances, their architecture, the variation in the required form of molecules, and the geometric relations between individual deposits required today in arrays enhances many fold the need for control. Each one of these parameters must be managed individually and often in combination with one another. Each category of input must be mastered as well as interactions between them, and as well as changes in a selection of parameters. Such a task is daunting even to a trained practitioner, and it certainly often escapes the capacity of individuals not specialised in manipulating a Dip-pen. The problem here then is to produce a tool that permits practitioners/customers with minimal expertise to use it. The creation of a kit constitutes one solution to this thorny problem. A kit may be seen as a device that permits unskilled users to cycle between complexity and simplicity.[7]

While the initial Dip-pen instrument research developed by C. Mirkin was relatively technically simple in comparison with the advanced devices later elaborated by NanoInk, it was nevertheless complex in its use due to many unknowns that marked its conception and the fickle operations of its then delicate and unstabilized components. There did not exist a format that allowed management of this simple apparatus, which consequently remained complex in its usage. By contrast, the Dip-pen subsequently researched designed and built by NanoInk is in fact immensely technically complex offering innumerable parameters and combinations of interactions. Nevertheless thanks to the company's creation of a computerised managerial format it became possible to translate through a plotter, innumerable parameters and permutations into a minimal, integrated and manageable body of simple commands, thereby permitting ready control. Complexity was gained through a form of reductionism − reductionism which did not diminish complexity but instead increased it inside each element.

The company engineered a software system termed the *translator* designed to control the Dip--Pen's hardware dynamics. This entails selection and control of the size and form of droplets, their spacing, geometric and

[6] One of the father of the AFM invented in 1986.

[7] Inken Rebentrost, *Das Labor in der Box. Technickentwicklung und Unternehmensgründung in der Frühen Deutschen Biotechnologie,* Scriftenreihe zur Zeitschrift für Unternehmensgeschichte, Verlag C.Hbeck, Band 16, 2006.

chemical relations, etc. The translator provides computerised control over all facets of production, making it possible for an unpracticed customer to produce his own extremely complex products through a series of simple managerial manoeuvres.

3. The mature firm and product commercialisation.

As the company grew, it moved beyond the need to focus on research for purposes of generating its own tool. Wwhile many of its resulting devices found outlets in research markets, it strove to identify an audience whose requirements were science independent and strongly anchored in societal preoccupations.
NanoInk has built five product divisions. A first division, The Nanofabrication division, manufactures devices in the form of kits. They are autonomous, self-standing and integrated devices, delivered to multiple users who then deploy their many permutations according to their diverse particular needs. The tool called the "Nscriptor" built by NanoInk, is a corner stone device for the company which serves in combination with numerous other NanoInk apparatus for the realisation of specialized tasks in research and applications.[8] "Nscriptor" is a device that deposits compounds in a specified dense pattern. It is harnessed to the "Inkcall' which translates commands introduced by the operator into the mechanical, temporal, spatial and chemical steps needed for controled deposition. The "Inkcal" user's controle over the intricacies of array productions. It may be considered as a kind of automation device. It serves to calibrate the deposition of NanoInk compounds, to control newly introduced inks employed in the "Nscriptor", and finally to research the deposition properties of previously unexplored substances.[9] Contrary to the "Nscriptor", "InkCal" is not an execution system, but instead based on the project of the user, it selects, calculates and calibrates the quantities and the sequence of deposition of the inks. In effect, it decides and controls the best way to achieve the user's projected objectives. The production of these two combined elements is the back-bone of all of NanoInk's activities. They figure in the other products and services offered by the company. This device is purchased for example by clients who use it in the repair of masks required for the production of electronic semi-conductor components.
The "Nscriptor" and "Inkcal" underpin the activities of the second NanoInk division _ the *Nanoguardian Division*. They are principally used for counterfeit protection, particularly with reference to pharmaceutical goods and possibly the labelling of currency. This technology codes individual tablets, with the place and date of production, date of expiration, and company trade mark. Medication can thus be traced and authenticated. Thereby nano materials and nano related competence contribute to the more general problem of standards of medical services and reduce the possibility of unwanted risks. More recently, this category of kit, the "Nscriptor" and the "Inkcal", is used to code individual bullets purchased by the U.S Military.
Two of the five divisions deal specifically with biological materials: the *NanobioDiscovery Division* and the *StemCell Division.* the *NanobioDiscovery Division* was established in December 2008. This division uses the Dip-pen to manufacture arrays specifically adapted to biological research which includes in combination with proprietary detection systems, the production of sensitive slides for protein discovery and identification. The kit

[8] http://www.nanoink.net/NSCRIPTOR.htm (3.11.2009)

[9] http://www.nanoink.net/d/technote_inkcal_software.pdf (3.12.2009)

“Just Add DNA” is a tool for generating multiplex DNA nano-arrays that can offer 10 to the 4th to 10 to the 5th times more features than conventional micro-arrays. As a result, a large number of biological targets can be simultaneously screened, and requires small amounts of materials. The whole device is delivered with tailored inks, cantilevers, inkwells, and protocols.[10] These products are sold, substrates and materials, to academic or pharmaceutical research laboratories (as detector arrays) where they are used for locally designed research.
The second biological division, the *StemCell Division* is also grounded on the construction of chemically and geometrically complex arrays. In this the Dip-pen technology is used to render precise nanopatterns capable of producing an homogeneous population of differentiated adult cells. Adherence, growth and differentiation of adult cells are dependent upon both the composition of the chemical cue and the pattern of the cues on the biochip. Examples of stemcell growth given by NanoInk include brain, fat, bone and cartilage cells.[11]
The final company division, the *NanoProfessor Division* established in mid 2009, is the result of an effort by NanoInk to develop a new dimension of its knowledge market. It is involved in education. The *NanoProfessor Division* extends the previous emphasis of the development and centrality of kits inside the company, and spread them out of a restricted scientific/technological circle. In effect, this division has developped a pedagogic kit as opposed to the investigatory and coding kits generated by the other Divisions.

4. Nanofication _ an emblematic instance of the societal strand.

In this phase, the societal and the enterprise strands of the helix intervene with the government’s strand which provides an environment. In phase three a tandem of strands consisting of enterprise and society prevailed where enterprise was dominant. Note that in the final phase of the Dip-Pen nanolithography innovation process, enterprise and society continue to dominate. However, here the hierarchic position of the two strands is inverted. The societal strand figures foremost and it is closely seconded by the enterprise strand. The inversion of the status of strands in these two phases, demonstrates the importance of the relational position of strands in the helix configurations. Reversal of hierarchy thus exercises a considerable influence over the content and direction of phases.
The NanoInk-professor program was launched during the internationally reputed Instrument Pittsburg Conference in 2009, where the NanoInk stand, and particularly the presentation of its teaching program, were publicly announced. According to the company and independent reports, this announcement was greated with massive interest. It almost immediately led to six confirmed pedagogic kit orders. Unanticipated by NanoInk, in addition to projected clients at the secondary school level, some technical colleges also exhibited interest and have purchased the teaching kit to train future nano-technicians.
The NanoInk Professor program and its relevant pedagogy and teaching manual, resonate with broader societal interests in nano-education.

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[10] http://www.nanoink.net/d/appnote_JustAddDNA.pdf (3.11.2009).

[11] http://www.nanoink.net/NanoStem_about.htm (09.20.2009).

The NanoInk concept of training in nanotechnology arose in 2007 and a new model of the Dip-pen specifically adapted to this purpose was developped. The NLP 2000 (Nano Lithographic Platform) is an example of simplification. This kit is robust, portable, and does not require the construction of a clean room which is unfeasable for high school and colleges.

The device and manual offer the possibility to undertake relatively simple operations at the nanoscale through the construction and manipulation of nano-arrays. On the most elementary level, it makes students at least aware of the existence of the nanoscale and may stimulate interest in the domain of nanotechnology. The Dip-Pen is accompanied by an elementary curriculum (101) level textbook specifically for nano-biology, nano-chemistry and nano-physics. According to NanoInk representatives, government money is sometimes available for finance and there exists pedagogical philanthropical institutes that have provided school districts with the required funding. One sees here the participation of the government as an environment to the society / enterprise binome that comprises this phase.

Nano Professor contributes to the process of nanofication on three levels: NanoInk's pedagogy is design to familiarise students in a general way with the vocabulary and idea of the nanoscale. In addition to this, it introduces information about materials and their properties. Students also learn how to operate some instruments and conduct experiments related to the nanoscale. It more over indicates domains in which nano has found applications and may lead to new ones. Not least of all, some instruction suggests possible career paths, particularly for technologists, competent in the nanoscale field. These are paths through which nanofication diffuses through different areas of society which include the economy, questions of ethics and risks, human kind's relations with nature, and eventually culture and mentality. By circulation of nano related knowledge, tools, techniques and skills, an ever expanding number and variety of groups are impacted, which in turn further transmit the fruits of their experience.

For several years, initiatives in nano instruction sponsored by universities, high schools, teaching bodies and some business organisations have attempted to develop course work specifically intended for learning in nano and for the dissemination of information about nano careers among students. Similar initiatives can be documented for the European Union, the Netherlands and Australia. In 2009, the international and interdisciplinary *Journal of nano education* began publication.

Some highly specialised research journals also occasionally publish education related articles, for example *Proceedings of The Society of Photo-Optical Instrumentation Engineers*, published in 2006 the article "Impressive virtual learning environments for nano science education: A paradigm shift" in which it militated in favour of nano-oriented high school education that would give students, rudimentary training in nanoscience and technology and would diffuse information concerning possible future careers in the domain [12].

A local professional high school teachers group oriented specifically to instruction in nano, I-test, was founded in 2007 by the graduate school of education at the University of Pennsylvania in Philadelphia. It involves forty

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[12] LightFeather, J AF LightFeather, Judith ED Lakhtakia, A; Maksimenko, SA
"Immersive virtual learning environments for nano science education: A
paradigm shift" - art. no. 63280 Nanomodeling II
SE PROCEEDINGS OF THE SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS
(SPIE) CT Conference on Nanomodeling II CY AUG 13-15, 2006
CL San Diego, CA

four districts in the region and its audience is high school students and their teachers. Among its aims are the familiarisation of students and teachers with the nanoscale, acquisition of concepts, and hands on experimental techniques, transition of information about the application of nano, and information on future careers possibilities in nano.
While it is not possible to evaluate the number of students and teachers involved in these various initiatives, nor to judge their degree of familiarity with nano, or determine how programs ultimately affect career trajectories, it is nevertheless clear that numerous nano organisation and firms and universities are committed to generalisation of the acquaintance by the public, with the nanoscale from a technical and scientific perspective. It is through such initiatives that the process of nanofication takes place[13].

The society strand of the first phase _ the reference to pen, parchment and ink_ that was conjoined to the university strand, is crucially echoed in the fourth phase. Mirkin's reference to the historical and cultural importance and functions of "writing", presently pragmatically extended to the nanoscale, is now fully embodied, having the broadest conceivable societal implications in the professor program, as commercialised and diffused by NanoInk Inc. The intelligibility of this case study would be curtailed in the framework of the erstwhile Triple Helix. By contrast through the introduction of the fourth societal strand, analysis of this complex contemporary events can be achieved.

Implications:

Examination of innovation practices in the above described instance of nanoscale research suggests that analysis in terms of the framework of the Triple Helix would in large measure mask some decisive features whose observation and explanation becomes accessible only through adding a forth strand, the societal strand, to the standard university/enterprise/ government strands. The question remains to what extent is it relevant or even

[13] Nano-oriented pedagogical reform is likewise growing outside the United States. Australia is developing a national educational program in nanoscience and technology directed at the secondary level. Like the Intist program at Philadelphia it is designed to establish convergence between biology, chemistry and physics, to introduce students to learning in nano, to demonstrate nano's affinity for applications and to inform youth about growing nano-related career openings (http://www.accessnano.org/about). The Netherlands is completing plans to introduce nano as one optional module in secondary school science teaching. Again nano will point to parallels between biology, chemistry and physics (Letter from Florine Meijer, project coordinator of nano instruction documentation University of Utrecht, Netherlands, to author, 9 April 2010). It would seem that among pedagogical reformers great attention is today being given to transversalities between disciplines. Finally, the European Union too now promotes educational programs in nano. These are directed at the bachelor, masters and doctoral level , with an eye to career potential in corporate technology (Ineke Malsch **"**Nano-education from a European perspective" Malsch TechnoValuation Vondellaan 90 3521 GH Utrecht, The Netherlands *Journal of Physics: Conference Series **100** (2008)*.

necessary to expand the triple helix into a quadruple helix for a larger sweep of innovation experiences? Does the societal strand offer supplementary analytic value mainly for events associated with nanoscience and technology? Alternatively, do societal issues today permeate domains beyond nanoscale research? If nanoscale research constitutes a particularly favourable terrain for the inclusion of societal matters, and hence the inclusion of the fourth strand, exactly why is this so in nano?

The careful reader of the Dip-pen nanolithography case study will have discerneds that in almost all instances, the active strands for each phase of the innovation process are organised in a binome. The introduction of this fourth societal strand has drawn attention to the organisation of innovation process in binomes where the less active strand stands slightly aside.

Phase 1 offers a binome of University/Society with the government providing an explicitly affirmative environment; phase 2 entails the binome of University/Enterprise; phase 3 stages the binome Enterprise/Society; phase 4 exhibits the inverted binome Society/Entreprise, with the government providing a favourable background. The reader will recall that we drew attention to the fact that the content of different phases in the innovation process does not solely depend on the presence of particular strands, it equally depends on the hierarchy between the strands.

The identification of these binomes invites reflexion on their structure and dynamics. For this purpose we draw selectively on some of the vocabulary and the concepts presented and analysed by Niklas Luhmann in his famous book “*Social Systems*” published in english translation in 1995 [14]. Among his analytical development, he describes one form of system which he terms “interpenetration”, where two subsystems commingle and in which each system constitutes the environment of the other subsystem and where there exists a larger ambient environment[15]. For our purposes, the study of the above noted binomss, is illuminated by the use of Luhmann’s concept of “interpenetration”.

We liken the subsystems of interpenetration to two strands in a Quadruple Helix configuration. An interpenetrating system consists of a receiver subssystem and a penetrating subsystem. In phase 1. the University was the penetrating subsystem and society was the receiver subsystem; in phase 2. the University was the penetrating subsystem and enterprise was the receiver; in phase 3. Enterprise is the penetrator subsystem and society is the receiver; phase 4. is characterised by an inversion of the binome of phase 3 where now the penetrator is society and the receiver is the enterprise strand. As indicated above, interpenetration systems possess a broader environment, and in the instances we have observed in this case study the environment often consists of a government strand.

In the case we explored, there is no evidence that a dominant strand functions alone, unaccompanied by an integrated associate strand. The strands that operate in interpenetration are inextricably linked, while each one nevertheless sustains its own subsystem identity.

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[14] Luhmann, N. (1995) *Social Systems* Stanford University Pess.

[15] His principle reflexion deals with a system which he defines as a relationship between system and environment.

Borrowing Luhmann's vocabulary, each of the two subsystems that constitute the dominant binome in a given phase, possesses its own specific expectations. The expectations of each subsystem (each "strand" in the parlance of the Quadruple Helix) reciprocally crosses one another and becomes meaning in the opposite subsystem, and in so doing, they combine and are reformulated as a transformed commonly held novel third expectation. It is the force of this recombined fresh expectation that organises each Quadruple Helix phase. The meeting and combination of these expectations may constitute the very motor of the innovation process.

It is possible that both the number of strands and their specificity, and the hierarchy between them, is of secondary significance when measured against the importance of the element of expectation as occurring in any subsystem, whatever it species and as expressed in the structure and dynamics of an Luhmann interpenetration system.