Collaborating on Convergent Technologies

Education and Practice

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ABSTRACT: Converging technologies will require collaboration across disciplines. A good metaphor for such collaborations is the kind of trading zone that emerges whenever human beings from different cultures interact. NBIC must avoid trading zones that are dominated by one discipline or set of interests and instead encourage multiple stakeholders to form a shared mental model of what needs to be accomplished. An example is drawn from current work on societal dimensions of nanotechnology. Students need to gain experience working in such trading zones, in addition to acquiring disciplinary depth.

KEYWORDS: collaboration; communication; trading zones; mental models; societal dimensions of nanotechnology; expertise; knowledge; capabilities

PRELUDE: THOMAS JEFFERSON ON CONVERGENT TECHNOLOGIES

The same artificial means which have been used to produce a competition in learning, may be equally successful in restoring agriculture to its primary dignity in the eyes of men. It is a science of the very first order.

THOMAS JEFFERSON TO DAVID WILLIAMS
NOVEMBER 14, 1803

Thomas Jefferson would, I think, bless our efforts to develop converging technologies. As the quotation above illustrates, Jefferson was a promoter of the 1800s equivalent of biotechnology. He experimented with multiple seed

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varieties at Monticello and he developed information tools like a portable copying desk, which allowed him to write two copies of a letter at the same time. He was interested in improvements in the information technology of his time: he treasured books. If he had known Richard Feynman, perhaps he would have been a promoter of nanotechnology as well. Jefferson valued independent cognition above all things, as we can see from a sentiment he expressed to Benjamin Rush on September 23, 1800: “I have sworn upon the altar of god, eternal hostility against every form of tyranny over the mind of man.”

AU: OK as re-expressed?

In this paper, I will sketch the conditions necessary to facilitate truly multidisciplinary collaboration, using concepts from cognitive science and the literature on science–technology studies (STS).

TRADING ZONES

Trading zones of the sort that arise when cultures exchange goods and information are a metaphor for multidisciplinary collaborations. Consider Eskom, one of the world’s largest utilities, which had to extend the electric power grid into the most remote areas of South Africa. Eskom developed a system in which residents of a village bought cards that allowed them to use a certain amount of power. Here the trade is simple; the villagers pay for power. But in this case, the money would leave the village without benefiting the local economy. Eskom tried to avoid this by training locals to attach homes to the grid, and also sell the cards, thereby contributing to the village economy. Unfortunately, these locals were caught in the middle of the kind of cultural divide that threatens trading zones. Their fellow villagers regarded Eskom as part of the former apartheid regime, and asked their local mechanics to do their part for the culture of resistance by hooking up homes for free (Cunningham *et al*., 1999; Gorman *et al*., 2000).

Peter Galison used the trading zone metaphor to describe the interactions among engineers and scientists that led to the development of radar and particle detectors (Galison, 1997). Baird Davis used it to describe the development of MRI technology (Baird and Cohen, 1999). To trade effectively, the different cultures have to develop a “creole,” or reduced common language.

> Two groups can agree on rules of exchange even if they ascribe utterly different significance to the objects being exchanged; they may even disagree on the meaning of the exchange process itself. Nonetheless, the trading partners can hammer out a *local* coordination, despite vast *global* differences. In an even more sophisticated way, cultures in interaction frequently establish contact languages, systems of discourse that can vary from the most function-specific jargons, through semispecific pidgins, to full-fledged creoles rich enough to support activities as complex as poetry and metalinguistic reflection” (Galison, 1997, p. 783).

Gorman and Mehalik (2002) proposed three major types of trading zones.

Elite Control Trading Zone

The first is controlled by an elite: those participants from other groups or cultures either obey, or they are thrown out of the network. The elite can be a group of experts who use their specialized knowledge to dictate how a socio-technical system will function. Communication is in the form of orders from the elite, and evidence of obedience from those below. An example is the imprisonment or execution of Soviet engineers who tried to think independently about major technological projects directed by Stalin (Graham, 1993). Another example is the failure of centralized agricultural schemes, which were excellent at controlling the behavior of villagers, but a failure at producing enough food for the population (Scott, 1998). Still another is the fact that famines do not occur in democracies.

> Famines kill millions of people in different countries in the world, but they don't kill the rulers. The kings and the presidents, the bureaucrats and the bosses, the military leaders and the commanders never are famine victims. And if there are no elections, no opposition parties, no scope for uncensored public criticism, then those in authority don't have to suffer the political consequences of their failure to prevent famines. (Sen 1999, p. 180)

In other words, elite control networks are a major factor in causing famines.

Eskom's plan to supply power to remote areas of South Africa was seen by villagers as this kind of elite control network, even though the company intended to create the kind of trading zone described in the next section.

Relatively Equal Trading Zones

The second type is a relatively equal trading zone, where all parties negotiate what they consider a fair exchange. Most democracies, for example, are trading zones in which leaders remain in office only as long as they convince sufficient voters to support them. In a democracy, the leaders experience at least the political consequences of a famine, and they are therefore motivated to respond (Sen 1999).

Eskom thought jobs and power offered a fair exchange for asking villagers to buy meter cards, priced within reach of their very small incomes. Now Eskom is in negotiation with villages to reconfigure the trading zone so that power will not be stolen. The point is that neither Eskom nor the villagers get to dictate the terms of the trade—they have to negotiate.

This kind of a trading zone includes a continuum, from limited, adversarial interactions where different groups of experts try to "throw their parts of a technology over the wall" to each other to a more constructive engagement among interacting experts who agree on common goals. AIDs research protocols served as a boundary object for activists, medical researchers, and statisticians, each of whom saw them in a different way. Initially, groups of activists demanded changes in the protocols and researchers made some concessions—a primitive trading zone, more adversarial than cooperative. But as activists grew in sophistication and attracted allies among statisticians, the trading zone became more collaborative and the activists moved from *reacting* to become what Collins and Evans call *interacting* experts (Collins and Evans 2002). For example, Epstein describes one activist who came into meetings with "seven earrings in one ear and a mohawk and my ratty old jacket on" and was dismissed initially as one of those street activists who had no expertise worth attending to (Epstein, 1995, p. 419). But when this activist showed her growing command of the technical language, she won respect.

AU: [her]?

Experts from different fields interacting around the development of a technology or system—like radar or MRI—see the system or object at the center of the zone in ways dictated by their disciplinary backgrounds. Surgeons viewed the MRI differently from the engineers who designed it:

AU: are the parenthetical expression in quote yours?

> …[I]t became fashionable for physicians to reduce the rather long MR (magnetic resonance) imaging times by using anisotropically shaped (i.e., non-square) imaging pixels in studies of the spine. As it turned out, this resulted in a prominent dark line appearing within the spinal cord. The dark line was a Gibbs ringing artifact. Unfortunately, clinicians, not aware of this kind of artifact—[from] not being conversant with the mathematics used to transform the instrument signal into an image—at times interpreted this artifact as a disease process: a fluid filled lesion known as a "syrinx" requiring aggressive medical treatment. (Baird and Cohen 1999, p. 238)

An expert who bridged medicine and physics identified the problem—too late for many patients. In this case, the "creole" among medicine, physics, and engineering was insufficient and needed to be modified by an individual who could cross the trading zone, acting as a kind of interpreter.

MRI and radar are examples of boundary objects at the focal point of scientific or technological trading zones. Different groups participating in the zone view the boundary object differently, as in the case of physicists and physicians working with MRI. Boundary objects are "most useful in analyzing cooperative and relatively equal situations; issues of imperialist imposition of standards, force, and deception have a somewhat different structure" (Bowker and Star 1999, p. 297). Therefore, boundary objects will be absent from trading zones that are dominated by an elite group, but are likely to exist in trading zones where the partners are relatively equal. In the Eskom case, for example, the company wants its metering technology to form a stable boundary object regulating trade, but the villagers see it as an imposition by an oppressive elite; therefore, they seek ways of circumventing the meter system.

Shared Mental Model Trading Zone

In the third kind of network, participants need to have a shared representation of the boundary system. In trading zones, people spend time trying to imagine each others' intentions, and also create and sustain different views of technological system on the boundaries, as shown by Bijker in his excellent work on technological frames (Bijker, 1995). Some parts of these imaginings are tacit—virtually impossible to articulate—and therefore cannot be completely captured in inscriptions or conversation. These tacit representations are frequent sources of misunderstandings in multidisciplinary trading zones (Gorman, 2002). I use the term *mental model* to designate both individual and shared representations that are partly tacit and typically have visual and/or kinesthetic components.

For example, I have shown how Alexander Graham Bell deliberately adopted a strategy he referred to as "following the analogy of nature" in which he based his telephone on the human ear (Gorman, 1997). Bell had extensive, hands-on experience with how the ear translated sound waves into mechanical motions. Bell's mental model was dynamic and evolved over a long series of experiments.

Similarly, convergent technologies are based on an analogy to how nature works at the nano scale. Researchers are developing mental models for nano devices based on biological processes. I contend that the most successful multidisciplinary groups will share these mental models across their trading zone. This kind of sharing will allow experts from different disciplines to contribute to a joint understanding of a problem domain.

An example of a trading zone around a shared mental model is the development of the ARPANET, which involved a growing network of practitioners at elite institutions (Hughes, 1998). ARPA's goal was to "find people that they thought were sufficiently smart and sufficiently motivated, give them a ball and let them run with it" (Hughes 1998, p. 287). Within this group, there was free, equal, and open exchange of ideas, leading to collaboration. But in order to break in, you had to be selected by one of the original champions. When asked how he knew what people and universities to fund, Joseph Licklider at ARPA said it depended upon "a kind of networking. You learn to trust certain people, and they expand their acquaintance. And the best people are at the best universities, which one knows by reputation" (Hughes, 1998, p. 264).

Therefore, the development of the ARPANET involved a shared mental model network, built around the idea of time-sharing, for those selected to be part of the elite development team. However, the selection process resembled the traditional "old boy's network." Similarly, genetically modified organisms were developed by a team at Monsanto that collaborated closely, but this technology looked to European consumers like an attempt by America scientists and farmers to dictate their food preferences. While it is fine for a small group of inventors or scientists to develop a shared mental model of a new technology, they need to include other stakeholders as early as possible—as in the design of the Boeing 777, where customers, engineers, technicians and others collaborated, from the earliest stages of the project (Rodgers, 1996).

In summary: The relationship between the three types of trading zone, three levels of expertise (Collins and Evans, 2002) and three levels of communication is shown in TABLE 1. In an elite control zone, there is no shared expertise, and communication is in the form of orders from the top and evidence for obedience from the bottom. In a relatively equal trading zone, experts from different disciplines learn a "creole" to interact around a boundary system that each discipline views somewhat differently. In a shared mental model zone, experts from different fields jointly contribute to breakthroughs that transcend any individual discipline.

TABLE 1. Types of trading zone related to level of expertise and communication

Trading Zone	Elite Control	Boundary Object	Shared Mental Model
Shared expertise	None	Interacting	Contributing
Communication	Orders from the top	Creole	Shared meanings

SOCIETAL DIMENSIONS OF CONVERGING TECHNOLOGIES

Converging technologies have the potential to improve human performance, but they may do so in a disruptive way that causes suffering to large segments of society. Therefore, we need to consider the societal dimensions of converging technologies from the earliest stages of development—not only to avoid ethical problems, but also to focus technology on global problems and opportunities. Let us consider how the three states could help us characterize the kinds of collaboration that could emerge when social scientists, ethicists, scientists, and engineers work together.

In an elite control network, converging technologies might produce benefits in human performance available only to a wealthy few in highly developed countries. Those without these enhancements might work at substandard jobs or live in poverty, as much of the world does now. Amartya Sen and others have established the benefits of spreading affluence and education across the globe, including the notion that this is the best way to limit population growth (Sen, 1994). Unless converging technologies benefit the whole planet, and not just an elite, we have failed to make real progress.

What if ethicists were allowed to direct basic research in converging technologies towards socially beneficial goals, regulating the research enterprise without significant input from the scientists or engineers? This would simply be another kind of elite control network. In this case, the likely result would be sub-standard science.

In a more equal trading zone, social scientists, ethicists, scientists, and engineers would develop regulations and rules for the ethical conduct of research across a trading zone that would include policymakers. Such rules are extremely valuable, but no set of rules can allow for every contingency, especially those created by the latest breakthroughs in technology. Regulatory bodies can try to adapt the rules to novel situations, but such bodies are usually adversarial and reactive. Monsanto successfully navigated the European regulatory framework when it introduced gnetically modified organisms (GMOs), but regulatory approval is not the same as consumer acceptance.

AU: OK as spelled out?

Regulatory trading zones will clearly be one of the way in which nanotechnology is kept within socially acceptable boundaries, but they are not sufficient. They will need to be accompanied by at least some situations where social scientists, ethicists, scientists, and engineers share mental models of where nanotechnology ought to go. In these networks, participants would explore the cutting-edge together, transcending their disciplinary expertises in novel ways. In the initial phases of such collaborations, the social scientists might serve as proxies for other stakeholders in the broader society, but these stakeholders would have to be brought in as soon as possible.

Societal Dimensions of Nanotechnology as an Example

The National Science Foundation is supporting a project at the University of Virginia that aims to create this kind of deep collaboration on societal dimensions of nanotechnology:

AU: spell out MRSEC

Robin Catalano, a student entering our MRSEC, has two advisors: a materials scientist (James Groves) and a social scientist (Gorman). Groves' expertise is in vapor deposition and metal oxide synthesis. Together, we are exploring how growing nanostructures on these oxides can be directed toward solving global problems.

While we are developing a shared mental model of our research goal, we divide labor within the team. Groves and Catalano explore the literature on metal oxides. Soon Groves and Catalano will make a transition to experimental explorations of metal oxide nanodot growth. Catalano and I work on the societial dimensions literature. All of us are involved in a constant knowledge exchange so that this division of labor will not result in an artificial separation of the social and technical. Each of us sends regulare e-mail messages reflecting on this experience to a cognitive scientist, Jeff Shrager, who has created a diary of his thinking processes as he became a molecular biologist <http://aracyc.stanford.edu/~jshrager/personal/diary/diary.html>. Shrager responds with questions that promote metacognitive awareness of our collective learning processes. In other words, he encourages us to think about how we are thinking about nanotechnology. We also plan on finding a way to map or graph our collective problem-solving processes.[a]

I have recently added two first-year honors engineering undergraduates to our societal dimensions project. I believe it is important to get science and engineering students involved in multidisciplinary research as soon as possible in their college careers, and keep them going on a project for four years, one to which they can apply their growing knowledge. This will be especially true of nanotechnology, an opportunity that cuts across typical disciplinary "stovepipes."

IMPLICATIONS FOR EDUCATION

The nanotechnology revolution may create as many as 800,000 jobs in this country alone (Roco, 2002). What do students need to know in order to participate in this technological revolution? Let us consider four types of knowledge (Gorman, 2002) involved in becoming an NBIC expert:

Information (the What)

Part of becoming an expert is knowing facts. For dissemination of facts, a State 1 classroom situation can be effective, in which the instructor dictates, and students learn to master the instructor's textbook knowledge and language. But one consequence of the information explosion is that we rely more and more on external memory aids for information: "Knowing where things are to be found can be a more important consequence of education than merely knowing things" (Wegner, 1986, p. 189).

Skills (the How)

Gilbert Ryle emphasized the distinction between skills (knowing how) and information (knowing that): "knowledge of how to perform tasks as well as knowledge of fact" (Vincenti, 1990, p. 13). John Anderson refers to Ryle's "that" as declarative knowledge and his "how" as procedural (Anderson, 1983). According to Anderson, procedural knowledge is encoded declaratively first, and then translated into procedures. However, there are many cases where procedures are learned by feel, or intuition, before they can be described—and aspects of these skills elude description altogether (Bechtel and Abrahamsen, 1991).

Procedures can be memorized and imitated in a State 1 classroom situation, in which the students are given a textbook laboratory or mathematical exercise

[a]Currently this is an informal learning study; we are seeking IRB approval to study ourselves in a more formal, organized fashion.

and required to reach the one right solution. The complex, nuanced skills of the expert are best learned in vicarious or actual apprenticeship experiences.

Judgement (the When)

Judgement is the knowledge of when a particular piece of information is useful, when it is effective to apply a particular skill, and when specific skills and information need to be combined. Expert physicists employ judgment to classify problems in familiar terms (Chi *et al*., 1981). Even when novices possess the necessary information and skills, they are unable to see how they apply to a particular problem. Expert knowledge is more than a "pile of facts"—it is structured in ways that facilitate problem-solving (Ericsson and Charness, 1994) and is embedded in the state of the art (Koen, 1985).

The transition from novice to expert is marked by a

> … progression *from* the analytic behavior of a detached subject, consciously decomposing his environment into recognizable elements, and following abstract rules, *to* involved skilled behavior based on an accumulation of concrete experiences and the unconscious recognition of new situations as similar to whole remembered ones. (Dreyfus and Dreyfus 1986, p. 35)

Judgement cannot be taught by rote; it has to be learned gradually in a series of trading zones in which the students interact with experts as they discuss cases or work on solving problems. That is why undergraduate research internships should be an important part of any NBIC initiative.

Wisdom (the Why)

Walter Vincenti quotes Philip Rhinelander's remark that wisdom is "the art of making correct decisions on insufficient evidence, under conditions of uncertainty" (Vincenti, 1990, p. 46). Therefore, Vincenti argues, "good design judgement clearly qualifies as a form of wisdom" (Vincenti, 1990, p. 46). Wisdom is the ability to reflect on *doing* or what is done, to question prevailing mental models and procedures and, if necessary, to come up with a new course of action.

AU: OK as re-phrased?

In terms of the societal dimensions of technology, wisdom also requires an element of moral imagination, which involves the ability to "go out toward people to inhabit their worlds, not just by rational calculations, but also in imagination, feeling, and expression" (Johnson, 1993).

Converging technologies will depend on discipline-based information, skills, and judgment. But NBIC will also require the kind of wisdom that allows the expert to understand the perspectives of other stakeholders, and share her/his knowledge with them, inviting intelligent contributions from any perspective. Hence, we want to encourage students to form networks or groups where they share their individual expertises and skills from the earliest stages of their time as students. They should also be encouraged to form a "big picture" of the advancing technological front, including the ways in which it might transform social systems, for better or for worse.

EARTH SYSTEMS ENGINEERING MANAGEMENT

The converging technologies initiative is currently a set of potential technological solutions in search of problems. At this early stage of technological development, it is particularly important to consider the challenges that face our species and planet over the next 100 years.

Let us consider an example involving an emerging multi-disciplinary trading zone that is motivated by global challenges and has a strong educational component. Brad Allenby, a prominent industrial ecologist, has called for the development of Earth Systems Engineering Management (ESEM) (Allenby, 2001). ESEM begins with the premise that no corner of the globe is unaffected by human beings, given our technological "advances," and therefore we have a responsibility to manage our planet intelligently. Human beings, nature, and technology are all closely coupled in a dynamic system whose interactions are hard to predict.

This kind of system cannot and should not be managed via an elite trading zone, in which resources are ruthlessly exploited or a particular environmental ideology is imposed on all participants. Instead, most environmental regulation involves a trading zone among multiple agencies with interacting expertise (Jasanoff, 1995). But ESEM implies moving beyond this kind of often adversarial regulatory trading zone to a continuous dialogue with the complex system that will produce shared representations—a dialogue that will include cognitive scientists, ethicists, environmental scientists, systems engineers, and policymakers.

Consider a complex system like the Everglades, home to 68 endangered species, multiple eco-systems, and a surge in human development. Managing such a system will require experts who are skilled at multiple disciplinary languages and who recognize the political agendas of competing agencies and stakeholders. These ESEM experts will not have a privileged view of the "true" system; instead, they will have to facilitate contributions from multiple experts and stakeholders.

Is this kind of ESEM expertise actually possible? The only way to find out is to try to create it. At the University of Virginia, Brad Allenby and I are teaching the first undergraduate course on Earth Systems Engineering Management. We draw students primarily from engineering and environmental sciences, but bring in lecturers from multiple disciplines, including architecture, business, conservation technologies, and ethics. The students spent the first part of the course learning the skills necessary to tackle complex human-natural systems. Then we form them into multidisciplinary teams to either design a new conservation area that will stretch from Yellowstone to the Yukon (Y2Y) or redesign the Everglades. We bring in additional guest speakers familiar with these areas.

These sorts of projects are typically considered far beyond the reach of most students—indeed, they defeat most experts. Students have the advantage of having no disciplinary boundaries; it is easier to convince them to look at the whole system. Typically, groups pick sub-problems within the system that force them to consider the whole, e.g., the design of wildlife corridors through Y2Y or the replacement of traditional dams with new technologies in the Everglades.

Converging technologies should play an important role in efforts like ESEM that are focused on improving our planet. One of the problems with complex dynamic systems is that you cannot predict with certainty how your interventions will perturb the system. Therefore, we need to develop better ways of collecting and processing data as well as reversible technologies that can be adjusted quickly when evidence of an unexpected consequence appears.

Another obvious global challenge is the divide between rich and poor around the world, which is reflected in access to technologies. I conduct my ESEM class in a computerized room where students have access to the Internet. The students are well-fed, healthy, and have excellent career prospects. The very computers they work on will be obsolete in several years, and may end up being dumped in China, where young people the age of my students will break them up by hand, exposed to toxins like mercury and lead, for about a dollar a day in salary (Goodman, 2003). The waste from this "recycling" leaches into the local water supply.

The biggest per-capita markets for new technologies will be among the poorest of the poor worldwide (Friedman, 1999). NBIC should focus on how these billions can be brought into the global marketplace of ideas and opportunities in a way that avoids the damaging environmental effects wrought by the first Industrial Revolution.

CONCLUSION

As Philip Kuekes suggested at NBIC Convergence 2003, these converging technologies could lead to a new Renaissance, where we follow the analogy of nature to the nano level, discovering a realm of knowledge built into our own bodies. Amartya Sen's (1999) work suggests that our focus ought to be on human capabilities, not just performance. Capability is very similar to opportunity, and harkens back to the Jeffersonian ideal that "all men are created equal." To rephrase the rhetoric of the Declaration of Independence, we might say that all women and men ought to have equal capabilities, and NBIC might put this ideal in reach. For example, those now physically disabled could have biotechnical performance enhancements that would allow them to have the same opportunities as others. Those born in relative poverty would have the opportunity to enter the global economy by having access to quality information and credit at fair terms (not the usurious rates charged by local moneylenders).

To create new technologies that extend human capabilities in beneficial ways, we will need to develop new ways of working together. This paper takes a step in this direction by advocating trading zones built around shared mental models. As we experiment with ways of forming these zones, we also need to study the processes by which we create them. Converging technologies require converging aspirations in which individual ambitions for particular disciplines, institutions, and careers combine into a whole that is greater than the sum of its parts.

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