Ontological Uncertainty and Innovation

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SFI WORKING PAPER: 2004-06-014

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This paper explores the relationship between uncertainty and innovation. It distinguishes three kinds of uncertainty: truth uncertainty, semantic uncertainty, and ontological uncertainty, the latter of which is particularly important for innovation processes. The paper then develops some implications of ontological uncertainty for innovation processes at three levels of organization, by means of three theories: a narrative theory of action at the level of individual economic actors; the theory of generative relationships at the meso-level of agent interaction; and the theory of scaffolding structures at the macro-level of market systems. These theories are illustrated by means of examples drawn from a prospective study on the emergence of a new market system around a technology for distributed control. The paper concludes with a discussion of the relation between theory, stories and models.

The authors would like to acknowledge the financial support for the research reported here from the European Commission IST-FET program, the Italian Ministry of Universities, Instruction and Research, and the Santa Fe Institute. We thank our colleagues in EC ISCOM research project and the participants in the SFI workshop on scaling and social organization for valuable comments and discussion.

This paper is about the relationship between uncertainty and innovation. In particular, it raises and responds to two questions: what are innovating agents uncertain *about*, and how does their uncertainty affect how they *act*? In section 1, we explain what we mean by innovation, with the help of an example to which we refer throughout the paper. In section 2, after some preliminary considerations on the relation between temporality and action, we describe a way of thinking about uncertainty. This idea leads to a distinction between three *kinds* of uncertainty: truth uncertainty, semantic uncertainty, and ontological uncertainty. Of the three, ontological uncertainty is the least discussed in the economic literature, but we argue that it is essential for understanding innovation processes.

The next three sections of the paper explore the relationship between ontological uncertainty and innovation, with respect to different time scales and levels of organization in agent space. Section 3 describes how individual innovating actors[1] manage to keep ontological uncertainty at bay, so that they are not paralyzed by their inability to foresee the consequences of the interactions in which they engage. By embedding their present context in a narrative structure and enacting their own assigned role in the resulting plot according to what we call narrative logic, actors may combine teleology with indeterminism – that is, have a sense for where they are heading, even if they cannot foresee the interaction pathways that will take them there. The rapid and unpredictable contextual changes that characterize innovation processes guarantee that sooner or later events get out of control and the actor's guiding narrative breaks down. However, the past is sufficiently plastic and narrative structure sufficiently rich that actors may then re-embed the new contexts in which they find themselves in a new story to enact.

In section 4, our focus changes to a longer time scale than the extended present of narrative embedding, to relations among agents rather than behavior of individual actors, and to constructive rather than cognitive processes. We argue that agents confronting ontological uncertainty cannot determine their strategies for the future solely in terms of attempted calculations of future profit or revenue streams. Rather, we introduce a new unit of accounting: the *generative potential* of their relationships with other agents. We then show how semantic uncertainty may emerge in the context of generative relationships – and how the resolution of this uncertainty may give rise to new attributions of identity that may then be instantiated in new artifacts or new kinds of agent roles and relationships.

In section 5, we again shift to a longer time scale and a higher level of organization. We show how market systems emerge through the construction of *scaffolding structures* in agent space. Through these structures, the agents who operate within the market system jointly confront their ontological uncertainty. Scaffolding structures provide a framework for *controlling* the kinds of new entities – both agents and artifacts – that enter the market system, and for *aligning* the attributions of agents in the market system about one another and the artifacts they make, exchange, install, maintain and use. Through scaffolding structures, agents can consolidate a zone of agent-artifact space, making it sufficiently stable to support both markets and the generation of new artifacts to be traded within those markets. At least for awhile…

1. Innovation: an example

In 1990, Echelon, a Silicon Valley start-up company, launched LonWorks®[2] distributed control technology as a "universal solution to the problem of control."[3] Since the "problem of control" arises whenever energy is deliberately applied to transform the state of a physical entity, Echelon's claim for

[1] We use the term "actor" for an individual human being, while "agent" may refer to any entity in the name of which action is carried out.

[2] Echelon, LonWorks, LonTalk, LON, LonBuilder, LonUsers, LonMark, Neuron, LonPoint, LNS, and LonWorld are trademarks of Echelon Corporation registered in the United States and other countries. LonMaker is a trademark of Echelon Corporation.

[3] Echelon (1990) is a video of the launch event, which took place in New York on December 7, 1990.

LonWorks technology was breathtaking in its scope. By the '90's, there were three established industries producing systems that solved the "problem of control" in particular contexts: building automation – primarily heating, ventilation and air conditioning, called HVAC, but also lighting, security and elevator systems; discrete control – routing and assembling components on the factory floor in manufacturing processes, for example in automotive or electronic fabricating plants; and process control – mixing liquids or granular solids in batch processes, for example in chemical plants or breweries. These industries were comprised of practically non-overlapping sets of firms, which produced, installed and maintained completely different sets of control devices and systems. Moreover, each had a distinct market system[4] organization, with trade associations, trade fairs, technical journals and standards bodies. Control technologies were of course very important in other sectors, in particular transportation, medicine and agriculture, but none of these had developed a separate "controls industry". Rather, system manufacturers in these sectors provided whatever automatic controls their systems required, perhaps with the help of subcontractors with particular control or communication competence. Finally, the most enticing, because potentially the largest, market of all for automated control – the home – hardly existed at all in 1990, as it hardly exists even today, despite a periodic media barrage lauding the glories of the "automated" (nowadays "networked") home and the imminent arrival of a huge multibillion dollar home automation industry.

According to Echelon, all these different sectors faced "control problems" that at least on a sufficiently abstract level were identical, and LonWorks technology provided the key to distributed control solutions that could work optimally for many or all of them. The LonWorks technology is based on the Neuron® chip, a low-cost integrated circuit that is easily programmable and contains the LonTalk® embedded communications protocol, which was designed to be optimal for control applications. With LonWorks technology, control systems can be constructed as a peer-to-peer network of communicating nodes, each containing a Neuron chip. The nodes can be attached to the various sensors and actuators in the system, and the Neuron chips programmed to collect information from sensors and transmit the data over the network to other nodes programmed to process the data, execute programmed control algorithms, and provide appropriate control values to actuators.

The distributed architecture made possible by LonWorks technology is radically different from the leading technological paradigm for control systems as of 1990. According to that paradigm, sensors and actuators were wired through a hierarchical set of data concentrators that route all information flow to and from a central controller, which contained one powerful computer programmed to execute all control operations, issuing control commands back to system actuators.

For Echelon, a distributed architecture was the next major step in control. In the previous two decades, computer architectures had moved from centralized proprietary main frame computers, to decentralized proprietary mini-computers, to personal computers interconnected over large peer-to-peer networks, with component parts based on open standards and available from multiple vendors. Since the underlying hardware and software technology for control systems was similar to those for computer systems, Echelon believed that the control industry could achieve the same benefits that had accrued to the computer industry from the move to distributed architectures: dramatically reduced hardware costs, substantially reduced wiring costs, scalability, and multi-vendor availability of components based on open standards.

Clearly, if LonWorks technology were to succeed in realizing Echelon's launch-time expectations, a new market system would have to grow up around it, penetrating and eventually subordinating the three established control market systems, and developing control products and systems appropriate for the home, factories, buildings, transport and much else besides. That is, success would imply cascades of changes:

[4] See section 6 below for a definition and discussion of *market system*.

- in the relationships among a huge number of new artifacts that would be integrated into old systems in new ways and into systems delivering hitherto unimagined new functionalities;
- among the host of agents that would be involved in developing, producing, distributing, designing, installing, and maintaining these artifacts and artifact systems; and
- in the organization of patterns of use, in which still other agents and LonWorks artifacts would be jointly embedded.

What we mean by the term *innovation* is the set of processes through which such cascades of changes in the structure of *agent-artifact space*[5] are realized. The time horizon for innovation may be quite long. In 2003, thirteen years after the launch of LonWorks technology and fifteen years after the founding of Echelon, the construction of a distributed controls market system around LonWorks technology is still far from complete, although a great many changes in various zones of agent-artifact space have already happened:

- Over 4000 firms have in some way incorporated LonWorks technology into their business activities.
- A number of new kinds of agent roles have come into being and are helping to structure patterns of interaction in an emerging LonWorks market system, some with official designations and certification procedures like "LonWorks Independent Developers" and "Network Integrators".
- Hundreds of products that enable LonWorks technology, and thousands that make use of it, have been introduced to the market: according to one estimate, the total revenues from the LonWorks market system in 2000 was around $1.5 billion.[6]
- A set of *scaffolding structures*[7] has been created to mediate various kinds of interactions among the agents that develop and use the technology, including: the LonWorld® convention, an annual trade fair with several thousand attendees; the LonMark® Association that seeks to ensure standards for system-level interoperability of LonWorks devices and subsystems; and national and regional users' organizations that publicize and promote the technology, as well as regulate the terms of cooperation and competition among member firms.

New agents, new artifacts, and new kinds of relations among agents and artifacts are not the only innovations[8] centered on LonWorks technology since 1990. *Attributions*, on the part of Echelon and other agents drawn into the LonWorks world, have changed as well:

- about what the technology is and how it combines with other technologies and artifacts to deliver functionality;
- about what kinds of functionality distributed control systems can deliver;
- about what "control" is;
- as well as attributions that the agents who work with LonWorks technology make about themselves, each other, and the LonWorks market system.

The cognitive processes whereby such attributions come into being are also essential ingredients of innovation, as are the communication processes whereby the attributions held by different agents are brought into alignment with one another, creating shared attributions of agent roles and market system

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[5] See Lane et al. (1996) and Lane and Maxfield (1997) for an introduction to *agent-artifact space*.

[6] The estimate was provided by the CEO of Echelon at the 2001 LonWorld meeting, Frankfurt, October, 2001. Another way of monitoring the growth of the market system is by counting the number of LonWorks nodes installed, which can be approximately measured by the number of Neuron chips – the hardware "heart" of LonWorks technology – sold: over 30,000,000 by the end of 2002.

[7] See Clark (1998), Lane (2002) and section 6 for introductions to *scaffolding structures*.

[8] "Innovations" means "something new created during an innovation process"; similarly for "an" or "the" innovation. Innovation refers to the innovation processes themselves.

rules that enable the establishment of stable patterns of agent interaction that underlie the emerging market system.

Identifying innovation with processes that generate large-scale changes in the structure of agent-artifact space is not a standard move,[9] nor is it without problematic aspects. For one, it is post-hoc: by our definition, we cannot determine whether a new artifact, organizational change or agent relationship is "innovative" until we see how extensive are the ripples to which it gives rise in agent-artifact space in the form of *other* new artifacts, organizational changes, agent relationships and the like. For another, without a careful description of just what constitutes the structure of agent-artifact space, and what sorts of processes such a structure supports, the definition is at best only suggestive, not rigorous. We defer this task to a subsequent paper. For our present purposes, neither of these issues needs to be resolved. The important idea to carry into the successive sections of this paper is that innovation is a set of processes, extended in time, which involve the construction of new agents, artifacts and attributions – and new kinds of relations among them. In this respect, the LonWorks case is exemplary.

In 1996, we began to study this case in detail. The information we obtained about Echelon comes from many sources: repeated interviews with Echelon executives and technical personnel, participation in various activities of the LonWorks market system including trade fairs and standards organizations, involvement in several projects in which LonWorks systems have been designed and installed, the collection of material from the trade and general press and internet related to LonWorks technology and, more generally, distributed control. In addition, one of us (RRM) has served on the Echelon Board of Directors since 1989.

2. Action, time and uncertainty

Any intentional human action is inherently temporal. It takes place in the *present*, it is directed towards a *future* transformation of certain features of the current context, and how it is carried out depends upon the actor's *past* experience. We can think of action as a bridge that actors construct in the present, linking their past towards a desired future. Of course, the consequences of any action are mediated through networks of others' attributions and actions, not to mention the immutable laws of physics and chemistry,[10] and so the new contexts in which actors find themselves after their actions may be far from what the actors intended. And the process goes on: in these new contexts, the actors act once again, based on their past experience, which has now been augmented by what has just occurred, directed[11] towards future transformations perhaps different from how they were conceived just before.

Subsection 2.1 considers how two familiar theories of action – action as the outcome of rational choice; and action as the execution of routines – deal with time and uncertainty. In two following subsections, we highlight several aspects of time and uncertainty that these theories do not treat, yet which play critical roles in the phenomenology of innovation: multitemporality and pluritemporality, discussed in subsection 2.3; and semantic and ontological uncertainty, introduced in subsection 2.4.

2.1 Time and uncertainty in two theories of action

[9] See Rossi (2003) for a critical review of the innovation literature. Examples of alternative definitions include Malerba (2000), Nooteboom (2002) and Lundvall et al. (2002).

[10] And sociology and economics, whose "laws" may not be immutable, but still may constrain what can happen.

[11] By "directed towards" or "directedness", we refer to actors' orientation towards a particular zone of agent-artifact space, in which the actors intend to induce some sort of a transformation that they hope will accrue to their benefit. In general, the actors cannot specify with precision either the zone or the intended transformation. When they can, we can speak of an actor's "goal." In general, we speak of their "directedness."

We can think of any theory of action, then, as a way of specifying how actors interpret the "context" in which they must act and their own directedness towards contextual transformations, and how these interpretations yield the selection of an action modality. For any particular theory of action, the uncertainty that the theory attributes to actors is represented by whatever the theory highlights as problematic in any of these elements: the way in which actors interpret their present context, how they would like to transform this context, what kinds of action modalities are available to them, and how effective in bringing about the desired transformations they regard each possible action modality.

To illustrate this idea, we sketch two theories of action, neither of which will turn out to have much to offer in innovation contexts, but which may help us to understand just what is at stake in specifying a theory of action and its associated concept of uncertainty. First, consider a totally routinized theory of action, for example for the actions of a subordinate in a strictly hierarchical organization – the "Prussian military" theory of action. The idea here is to standardize action so that in any given context, a subordinate's action is – according to the view from the top of the hierarchy – appropriate and effective. Thus, the subordinate's actions are reduced to a complete and consistent set of stimulus-response pairs. To achieve this standardization, rigorous training must shape the subordinate actors' past experience in such a way that the right action modalities are in place (and only the right ones!), interpretations of context can be simply and unambiguously identified with the appropriate stimulus condition, and the subordinates' directedness corresponds exactly with the "grand" objectives of the top hierarchs. Assuming that this level of standardization and training can be achieved, the theory does not attribute *any* uncertainty to subordinate actors.

Of course, it is not easy to implement a training program that can generate such a top-down determination of action: sometimes, for example, a soldier's directedness in battle can be aligned with his officers' only by draconian measures like the threat of summary execution on the battlefield. Another, perhaps more basic, difficulty with this theory of action is that top hierarchs may not have sufficient understanding of the contexts that their subordinates may encounter, and so their standardized scheme for classifying contexts cannot function, and subordinates are essentially left to their own devices. This is part of the story that Orr (1996) tells about the Xerox repairmen and their bulky but rarely consulted work manuals. In any case, this theory of action certainly has very little to say about how top hierarchs act, unless we regard *their* actions as determined completely by "frozen" routines inherited from their own and their organization's distant past – and even then, one would probably want to develop a theory about how such routines develop.[12]

As a second example of a theory of action, consider Savage's decision theory. Here, the "present" contracts to a single point in time, the point at which actors choose which action to take. At the moment of choice, actors interpret their context to determine sets of prescriptions for available actions and possible consequences that might follow from each of the prescribed actions. The theory takes these tasks as unproblematic and provides no guidance on how they might be accomplished. Now uncertainty enters the theoretical picture: actors do not know *which* of the possible consequences associated with their available actions will actually occur, and so they must evaluate how likely each is to happen, as well as how attractive each will be, should it happen. Presumably, these evaluations are based on the actor's past experience, and Bayesian probability updating is often considered as a way of keeping coherent account of changes in evaluations of uncertainty as experience accrues over time. The theory takes these determinations as input and provides an algorithm to compute which action is preferred, and this action is then implemented as prescribed.

This theory presumes a great deal of fungibility between the past and the future: what actors have already experienced of their world is sufficient to equip them to foresee the kinds of things that can happen in the future – and even the value that these things will have for them, when they happen. In

[12] Some routine-based theories of action do try to describe such processes (for example, Nelson and Winter, 1982).

addition, the theory presumes that actions are sufficiently well specified in the present that implementing any of them, once it has been chosen, is automatic. All the difficulties here are in the present – the past is legible; the future, while it may not be foreseeable with certainty, is expressible in the form of well-defined propositions. To act is to choose, and choice is just a calculation.

2.2 Temporality in innovation phenomenology

It is, of course, part of the business of theories to abstract away from direct and detailed descriptions of the phenomena they purport to explain. However, both of the theories we have caricatured in the previous subsection parse action in time very differently from what we observe if we follow what goes on at Echelon. There, action happens *over* time, and how it develops is not scripted in moments of choice, but emerges through interactions among actors. The "present", that is the time in which action happens, does not contract to a point, but has *extension* through time. Moreover, action has an organization *through* time, in the form of *interaction streams*, linked sequences of events, in which a set of participants that share some aspects of their directedness engage with one another to achieve a transformation in some particular zone of agent-artifact space.

Different interaction streams may provide very different extensions to the present. Some interactions streams die almost as soon as they are born – for example, after a single meeting, in which representatives of two or more companies meet to discuss a possible joint project, and nothing more ever comes of it (even when the meeting seemed full of promise to all the participants – but one of them had arrogated to himself a permission exercised during the meeting that was challenged and then rejected by his superiors back at company headquarters, bringing the interaction stream to a full stop). The duration of interaction streams may vary over several orders of magnitude of time. For example, from August, 1989 until February, 1991, various Echelon employees began to work with employees of a major furniture manufacturer to develop a line of "smart office furniture", featuring smart locks for security management, smart electrical outlets for energy management, and personal environmental management capabilities. Echelon participants included the CEO, the Vice President for Marketing, the Vice President for Engineering, and the CFO, who met in various configurations with their opposite numbers in the furniture company to negotiate the conditions for the successive stages of cooperation between the two companies. This 18-month interaction stream suddenly "dried up," when a new CEO at the furniture company decided not to sign a contract that the two companies had already drawn up. Early in the collaboration, engineers from the two companies worked together intensively in October and November to develop a feasibility plan that was presented to their management in early December 1989 – a two month interaction stream, resulting in the successful completion of a plan that the management groups approved. At any given moment, actors may be immersed in several different interaction streams, each with its own time-scale – a situation that we call *multitemporality*. To illustrate multitemporality, we describe a few of the interaction streams in which one member, call him CM, of Echelon's marketing group was immersed in the beginning of 1995. CM's responsibility was to develop LonWorks opportunities in home automation. As we have already seen, there was a lot of talk about home automation through the 90's, replete with optimistic predictions about a market explosion "soon" – but not a lot of products or evidence of consumer demand. Potential home automation purveyors realized that they would have to form coalitions of companies that could put together systems featuring consumer electronics, computers, appliances, control technology – and maybe more. Thus CM spent most of his time with representatives of other companies discussing projects that might help ignite the expected explosion. At the beginning of 1995, he was still communicating regularly with counterparts at a major personal computer networking company. This interaction stream had begun in 1993, when a business development manager at the networking company had called up an Echelon salesman to discuss his company's initiative for networking “beyond the computer”. After a few months of preliminary discussion top executives from both companies met for several days to explore the possibilities. Both CEO’s endorsed a joint project to develop a concrete plan, and teams from each company were established. By early 1994, though, a new CEO was brought into the other company, and the ensuing reorganization affected adversely the progress of the joint project. Meetings between two companies became less frequent and unfocussed. Eventually Echelon’s CEO contacted his new counterpart and explained the potential importance of the alliance. Meetings recommenced, but due to changed priorities of the new CEO, discussions never regained momentum, and the project eventually was dropped. This interaction stream lasted for more than two years, but never led to a productive outcome.

Just as the interactions with the networking company were winding down, one of the top Echelon marketing managers and counterparts from Intel decided to respond to a request from a group at Computer Associates, the world’s second biggest software company, to jointly develop a project for the annual Comdex computer trade show, demonstrating a home networking system. This project had a definite time limit, November 1995, and required an intense collaboration of marketing and engineering people from each of the three companies. A division of Computer Associates, 4Home Productions, developed all the software, and the demonstration at the trade show was, according to CM, a great success. Many companies, from computer manufacturer HP and Packard Bell to home OEMs including Molex, Leviton and Harmon-Kardon, through distributors like Circuit City, were interested in jointly developing and marketing a set of products derived from the demonstration. Unfortunately, this phase of the project did not end successfully – negotiations dragged on through the early months of 1996, but the CEO of Computer Associates, who at the last minute had decided not to come to Comdex, didn’t evidence much enthusiasm for the project, and the computer manufacturers were swamped by other problems at the beginning of 1996, so nothing happened. This interaction stream had an intense and productive four-month initial phase, followed by 10 months of sporadic and ultimately unsuccessful discussions over possible further developments.

Meanwhile, exactly during the months when the discussions with the network company were waning, and work on the home automation demo was heating up, CM had to work fast to prevent a potential alliance between Microsoft and Compaq, around a home networking system based upon CEBus, a rival communication and control technology (see section 6). CM rallied the LonWorks allies in the home automation business to successfully convince these giants not to bet on CEBus. This successful interaction stream lasted only a couple of months, a period of frenetic activity that might have helped to ward off a serious threat to LonWorks technology. CM’s work situation in the fall of 1995 is typically multitemporal – each item with its own time scale for duration and frequency of interactions.

In addition, particular events may be linked by at least some participants into more than one interaction stream, so that the same action may have “downstream” consequences at different time-scales as well, which we call *pluritemporality*.[13] For example, in January 1994, Echelon participated, along with about 30 other information technology companies, in a Hollywood media event sponsored by Oracle, the giant software data base company, celebrating the “Information Superhighway”. Oracle was in this period trying to compete with Microsoft for leadership in the information technology industries. The event, “Silicon Valley meets Hollywood,” was intended to provide credibility and presence to Oracle’s strategy based on the idea of “network computing,” which at the same time would accelerate the re-centering of computing from local networks of personal computers, to large-area networks (and maybe even just one big network), with servers connected to myriads of relatively cheap “network computers”, able to access and execute software job-by-job from cyberspace – and, of course,

[13] Here the hydrological metaphor fails: merging water streams don’t reseparate, but interaction streams may intersect and then diverge without losing their separate identities.

data from big Oracle data bases running on powerful servers "in the sky". Echelon was invited to show that Oracles' "revolution" entailed a lot more than just data processing: all kinds of *devices* could be connected to the network as well, they could be remotely controlled to do what you wanted them to do, and they could send you information confirming that they were doing what you wanted them to do, no matter how much physical distance might separate you from them, whether you were a factory manager, the CEO of a huge multinational company, a homeowner, or a financial trader.

Echelon's demonstration for the Oracle media event featured remote energy management, and it made the most of the considerable number of news reports that Oracle marketing people were able to generate out of the event: good for Echelon, and good for Oracle, at least in the short term. Although Oracle's particular vision did not immediately take off as hoped, it eventually brought about a complete shift in Microsoft's strategy, realizing itself in the internet revolution of the late 90's, and many of its elements are now among the leading features of today's information technology's dominant paradigm. For Echelon, several of its consequences reverberated for quite some time. First, Oracle liked Echelon's demonstration, and the Oracle Utility Practices Group convinced the powerful electrical industry research organization Electrical Power Research Institute (EPRI) to organize a working group to propose an industry-wide solution based on Echelon's demo. The group was formed and initiated discussions, but nothing tangible came of its work.

Second, some people at Detroit Edison, a big Midwestern utility company, had also been impressed by the Echelon demonstration. They received permission from the highest level of Detroit Edison management to start negotiating for a joint project in "demand side energy management" based on LonWorks technology. This project went quite far. In fact, in 1996 Detroit Edison made a large investment in Echelon, and the two companies embarked on a big pilot project on demand side management. For reasons unrelated to the success of the pilot project, Detroit Edison decided not to pursue this initiative further. However, what Echelon did and learned in its work with Detroit Edison led indirectly to a contact years later with ENEL, the Italian energy provider about to confront the traumas of deregulation. The ENEL-Echelon relationships produced, in 2000, in the largest project and deal in the history of Echelon and LonWorks technology, the installation "intelligent" meter readers based on LonWorks tehnology in 27 million Italian households, a project that will be completed in 2005. This series of episodes illustrates the concept of pluritemporality: consequences of the same events may spread widely, through different interaction streams and different time scales.

2.3 Three kinds of uncertainty

We now turn to the relationship between uncertainty and action in innovation processes. We begin by distinguishing among three kinds of uncertainty, which differ according to what sort of thing the actor is uncertain about: truth uncertainty, semantic uncertainty and ontological uncertainty. They are not necessarily temporally or contextually mutually exclusive: multitemporality and pluritemporality imply that actors might confront all three in the *same* action context. The key point is that all three play fundamental, though different, roles in innovation processes.

In *truth uncertainty*, actors are uncertain about whether well-defined propositions are *true* or not. As we have seen, truth uncertainty is the only kind of uncertainty that Savage's decision theory admits, where the propositions in question are statements about future consequences. Savage's decision theory (Savage, 1954) claims that the truth uncertainty for all such propositions can be measured in the probability scale. Others maintain Knight's distinction between risk and uncertainty: propositions about risk are probabilizable by reference to a series of fungible propositions with known truth-values: while others, "truly" uncertain, refer to events that have no such reference set and hence, according to Knight (1921), their truth uncertainty cannot be measured probabilistically. For De Finetti (1930), the distinction is different: propositions whose truth conditions are observable are probabilizable, otherwise they are not. While controversy still smolders about just what the proper domain of probability is, it is certainly restricted to truth uncertainty: the other two kinds of uncertainty are *not* probabilizable.

In *semantic uncertainty*, actors are uncertain about what a proposition *means*. There are various kinds of circumstances in which semantic uncertainty may arise,[14] but by far the most important is when, in discursive interactions among actors, one participant comes to understand that another imputes a different meaning to some term, phrase, or event than his own.[15] All children experience semantic uncertainty as they learn language, when they encounter polysemy and learn to deal with the consequent ambiguities through interpretation of the context of use of words with multiple meanings. Such discoveries are very important also in innovation, because they may open up for examination concepts and attributions that actors had previously considered aspects of *reality* rather than "just" their interpretations. With this opening, it may happen that participants can jointly construct *new* meanings.[16] Generating new meanings, particularly new attributions of functionality for artifacts and new attributions of identity for agents, is an important part of innovation. *Becoming* uncertain in this sense may be consistent with actors' directedness, in interaction streams in which participants seek to explore their attributional heterogeneity, without precise foreknowledge of just where the heterogeneity lies and where its exploration may lead (Lane and Maxfield, 1997). So *reducing* uncertainty, often cited as the *ne plus ultra* in the economic and business literatures, may be just the wrong thing for innovative actors to do.

The definition of *ontological uncertainty* depends upon the concept of actors' *ontology* – their beliefs about

- what kinds of *entities* inhabit their world;
- what kinds of *interactions* these entities can have among themselves;
- how the entities and their interaction modes *change* as a result of these interactions.

Since structure on all levels – from elementary particles through cities and continents to galaxies – is dynamic, what counts to actors as an entity depends on the *time-scale of the processes* through which they think that their actions will generate effects. Actors commit the *fallacy of time-independent ontology* when these processes take place over different time-scales than those in which posited entities exhibit the requisite stable structure to count as entities.[17] For example, in the early-80's, shortly after the IBM pc entered the market, when a word-processor was an elaborate piece of special purpose hardware rapidly replacing the electric typewriter in "offices of the future", the founder and CEO of a leading word-processor manufacturing company declared to one of us (RRM) that there was no way

[14] Another is predicate uncertainty, where a predicate is used which lacks a definite meaning: "big", for example. Sometimes, this may just be an example of ambiguity, when two different actors interpret "big" with respect to different scales of measurement; in other occasions, it may be a way of avoiding false precision and its indefinite meaning may be socially shared. Fuzzy logic treats situations like the latter. Another example is a term that may a well-defined meaning, yet has consequences for action – as when a person wonders whether or not she is "in love" with another. While it is very doubtful that she could say exactly what being "in love" means, she is likely to act very differently should she resolve her uncertainty positively, than if she were to do so negatively!

[15] Agar (1995) discusses a similar idea, around his theory of "rich points."

[16] Not necessarily shared, by the way. Each may add some new conceptual dimensions and transform their own previously held interpretations, without generating the same interpretation between them. There are other process whereby different interpretations may be made to converge, and these communication processes are also very important in innovation, since they provide a basis of shared attributions about artifact functionality and agent roles that are preconditions for the construction of impersonal market structures. We return to this issue in section 6.

[17] Examples of this fallacy abound in economics, as in many other sciences, from analyses that assume equilibrium and ignore adjustment processes, when the action of interest may occur precisely during these processes; to asymptotic analysis that assume that strategies change while the rules of the game stay fixed, for situations in which rules change on the same time scale as strategies change. Hacking (2002) discusses some related ideas and further examples.

that his company's product's functionality could be delivered in the foreseeable future by software running on a general purpose pc.

Sometimes the entity structure of actors' worlds change so rapidly that the actors cannot generate stable ontological categories valid for the time periods in which the actions they are about to undertake will continue to generate effects. In such cases, we say that the actors face *ontological uncertainty*. Ontological uncertainty, in contrast to truth or semantic uncertainty, resists the formation of propositions about relevant future consequences. The entities and relations of which such propositions would have to be composed are *simply not known* at the time the propositions would have to be formulated – that is, during the extended present in which action happens. In the fast-changing emerging market system around LonWorks technology, ontological uncertainty is an endemic situation. Sometimes, ontological uncertainty hovers around an unaware actor. Sometimes, though, market system actors are completely conscious that they are immersed in ontological uncertainty, which of course gives them no particular help in dealing with it.

3. Enacting stories: towards a narrative-based theory of action

How can actors cope with ontological uncertainty? Clearly, neither routines nor rational choice are viable methods for generating action in the face of ontological uncertainty, since the propositions that describe the stimulus conditions for routines, or the relevant consequences of possible actions for rational choice, cannot even be formulated in the extended present when action occurs. This section outlines an alternative theory of action, in which narrative replaces analysis of future consequences in orienting individual actors towards the future. The central concept of the theory is the idea of narrative embedding: actors hold ontological uncertainty temporarily at bay by interpreting the contexts in which they must act in terms of stories whose structure is familiar from their past experience, and then they follow narrative logic, enacting their role in the story. Subsection 3.1 introduces the ideas of narrative structure and narrative logic, subsection 3.2 describes narrative embedding, and subsection 3.3 shows the relevance of narrative to action in the face of ontological uncertainty. Subsection 3.4 then illustrates these ideas by means of an example from our Echelon research. In the final subsection, we explore an epistemological problem that our theory must confront: how can we make inferences about actor *cognition*, on the basis of information obtained through *communication* processes?

3.1 Narrative structure and narrative logic

Narrative is the linguistic form we use to communicate human experience and render it meaningful to one another and to ourselves.[18] A narrative relates a series of events, with, as Aristotle pointed out, a *beginning*, a *middle* and an *end*. More specifically, a narrative consists of a cast of characters, a plot that structures the events temporally, and a denouement in which the fortunes and even identities of some of the characters change from what they were at the story's beginning. The characters' identities can be crudely but usefully summarized as "what they do and how they do it". Plot development consists of the characters acting out their identities in contexts that are determined by their previous actions, the actions of the other characters, and events from the world outside – including coincidences and catastrophes (wars, market crashes, floods…) that the narrator and listener regard as "normal," that is consistent with some implicitly agreed-upon natural or social "laws", and beyond the control of the story's characters.[19]

[18] There are rich literatures on narrative from a number of points of view – literary criticism, psychology, philosophy and anthropology. Our account of narrative draws in particular on the following works: Polkingthorne (1988),Ricouer (1990); White (1980,), Mink (1980), Carr (1986); Bruner (1987, 1992), Neisser (1994), Mishler (1999), Schaefer (1980); Propp (1968). Zappia (2003) presents an incisive critical survey of the literature on narrative.

[19] The implicit agreement need not go beyond the boundaries of the story-telling itself. Many of us may read novels of science fiction or magical realism, and we are perfectly willing to suspend our disbelief about how the narrator manipulates

Narratives do not just relate, they explain. The key to causality in narratives, the explanatory heart of a story, is character identity. A character's actions make sense to the listener because given who the character is and the situation in which he finds himself, no other actions seem as credible. Of course, the listener learns about characters' identities through their narrated actions, so there is a circularity here. We can resolve this circularity through two considerations. First, the listener's realization that a new action has in fact been determined by the actor's identity is retrospective, in the sense that the attribution of actor identity to which the action must cohere is determined *after* the listener knows about the action. Second, the listener has an implicit set of allowable transformations of identity, and if the narrated action cannot be successfully integrated with a reinterpretation of character identity by allowable transformations of the listener's attributions of character identities, the narrative fails, at least for that listener. So for a narrative to work,

- narrators must be able to present their stories as a succession of events in which their characters act and interact;
- the context of these events must make sense in terms of what actors have done in previous events and with respect to some natural or social "laws" that the narrator shares with his listeners; and
- within these events, each character's actions must be interpretable as a consequence of his identity, as determined by the listener from what he has learned about the character from the narrator – who in turn must respect his listeners' ideas about how identities, and hence attributions about identity, may change over time.

We subsume these three aspects of successful narrative under the rubric *narrative logic*.

We seem to be asking a lot from our story-teller: to construct shared laws of physics and society, as well as psychological theories about how identities change, is clearly too much to do while relating a sequence of events. In fact, the story-teller couldn't possibly do all that work in real time; the work is accomplished, off-line, by a social-level entity, which we can call a *narrative community*. Narratives can only work within particular narrative communities, groups of people who already share a set of *narrative structures*. A narrative structure is a kind of template for narratives. It consists of a set of *character types*, abstract descriptions of identities; *plot elements*, which consist of a set of allowable transformations for character identity, as well as the physical and social laws that determine how contexts may change outside of the characters' control and what kinds of coincidences are "normal"; and a skeletal *denouement*, in which the character types collect their "just deserts" – that is, rises or falls in fortune, and the achievement of certain kinds of merited relationships with other character types. Particular narratives instantiate one of these narrative structures, and when narrators and listeners are from the same narrative community, the stories can be told in such a way that all recognize early on just which narrative structure serves as their common referent. Narrative structures are cultural facts of narrative communities. They provide narrative with its rules of syntax. Like language's syntax, these rules aren't learned as explicit rules, but are abducted from the many stories instantiating them that circulate in the narrative community, to which members of the community begin listening as infants and continue listening, and then telling, throughout their lives.

Within a narrative community, narrative logic implies a plot development coherent with rules for character and action from one of the community's available narrative structures. We have seen that narrative structures specify abstract forms for a story's "beginning", in terms of the set of character types whose interactions generate the story's plot, and its "end", the denouement – but leave the "middle" open to many possible pathways, constrained just by the rules of allowable transformation. Thus Aristotle's three narrative categories have causal, not merely sequential, relations among them,

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physical law and contrives coincidental meetings among characters. When the narrator pushes the listener beyond the bounds of suspended disbelief, the listener stops listening.

which are by no means of equal importance: the "middle" is the bridge that connects the "beginning" to the "end", but to a large extent the "end" is already immanent in the "beginning". That is, denouement and characters are linked by narrative logic, which, as we have said, is a logic of causality by character, mediated through context: we know that Oedipus' hubris will inevitably bring about his fall; that a Jane Austen heroine, separated as she is by social distance and misunderstanding from the hero she loves, will eventually find happiness in his arms; that the saintly martyr will receive her final reward in the other world, after undergoing horrible tribulations in this one. Even though we can foresee in its broad outlines what the denouement of the story will be, once we have recognized the type of narrative structure to which it belongs, the story itself can be full of surprises, maintaining our breathless interest all the way to the end. This is the beauty and most important attribute of the narrative form: it combines *teleology* and *indeterminism*, leading the listener on a journey through time with a recognized and fitting destination, without providing a detailed route map of all the excitement and complications to be encountered along the way.

Narrative time is not uniform and featureless. In narratives, time is bunched into discrete "events," temporally and spatially circumscribed settings in which some kind of confrontation among the story's characters takes place.[20] Within events, the relevant characters interact, and the consequences of their actions propel them into further events. Thus events become linked together in interaction streams, identified by the subset of characters that interact in them and the causal shaping of successive contexts that the stream flows through. The duration of and between events – and interaction streams – can vary tremendously within a narrative. Longer narratives may consist of many interaction streams, flowing separately, then merging – and perhaps separating once again. In the end, all the remaining interaction streams flow into the denouement, or disappear into the trackless sands of the unresolved.

3.2 Narrative embedding and action: backing into the future

A rich and growing literature shows how important are autobiographical narratives for endowing one's own experience with significance.[21] Here, we consider a stronger claim: that narrative can be *constitutive* of experience itself. We posit a cognitive process, *narrative embedding*, through which narrative logic generates action.

In narrative embedding, actors' current context are framed in terms of one of the narrative structures of their narrative community, instantiated in remembered narratives from the actors' own experiences or learned from memory artifacts like books, cinema, and newspapers. The process picks out a cast of characters from the entities[22] in the actors' world *including the actors themselves* , builds up a plot that interprets prior events involving these characters consistently with the structure's allowable transformations, and associates a denouement that, in particular, foretells whether the actors come out well "in the end." Usually, the process works by a direct transfer from the elements of one remembered story to the present context, but it can also operate on the merger of more than one remembered narrative that share a common narrative structure or by "extending" a remembered narrative to incorporate additional characters. The process is not conscious, nor even, necessarily, are the narratives that it produces.

Through narrative embedding, actor-narrators make sense of context, find themselves in mid-story, and proceed to act out their assigned role assigned. As the plot rolls on, actor-narrators may be surprised occasionally by what the other characters do. They understand, however, as does any reader

[20] Sometimes a single character confronts himself – like Hamlet's soliloquy, or Beckett's Un-nameable, alone on the floor in the dark.

[21] See in particular Neisser (1994), Bruner (1987 and 1992) and Mishler (1999).

[22] Agents and artifacts, or even other entities – like Lady Luck, an anthropomorphized "market", or divinities, that are legitimate character types to some narrative communities, absurd to others.

of novels, that their current attributions of identity to the other characters must have been incomplete. They can then modify these attributions to account for the new plot-twist, perhaps drawing upon other, previously un-narrativized but remembered past events, as long as they do not violate the allowable transformations of the embedding narrative structure.

With respect to their own roles, actor-narrators have a privileged position. Their *own* actions are very unlikely to surprise them with new revelations about their own identity.[23] Thus, their actions tend to be comprehensible in terms of the ongoing plot they are following and their own self-attribution of identity. As a result, actor-narrators enact the story they tell themselves is happening. In this way, as long as the story continues to make narrative sense, its telling-in-action sweeps the actor-narrator along with it. Their actions, we can say, are generated by narrative logic.

Acting thus, actor-narrators are constantly looking backwards, reinterpreting everything that is happening in their extended present, in terms of the emerging story that they tell themselves to account for what is going on. Their own actions follow on and extend this continual reinterpretation, and as long as the story continues to make sense, they need not consider exactly where they are going – the denouement of their story takes care of that – so much as where they have just been. They are, in this sense, *backing into the future*.

Narrative embedding implies a strong downward causation from stories to events. Stories can supply missing events required by the exigencies of plot, which can be as credible to actors as the events they have actually experienced (Neisser, 1994a). As a result, narrative logic may permit actors to "know" much more than they can actually observe, and consequently to take action, directed by the logic of their stories, with more confidence than they might have were they to rely only on what "actually" happened, instead of the sense their story made of these events. Arguably, this extra confidence may translate into more effective action. On the other hand, what actors experience as "actually happening" depends on interpretations framed by narrative logic, so stories tend to produce concordant events – and not just on the part of the actor-narrator. For example, the suspicion that another character in the story is behaving badly to the actor-narrator can induce the actor-narrator to act in such a way that this will indeed turn out to be the case, producing new events that vindicate the judgments the actor-narrator made about previous events, regardless of the other's real intentions in the past. Thus, narrative logic may *enable* effective action, while it *constrains* action possibilities to those that make narrative sense.

We do not want to argue that *all* action is generated through narrative embedding – there may be many different action-generating modalities. However, we claim in the next subsection that narrative embedding provides actors with the means to deal, at least in the relatively short-term of the extended present, with ontological uncertainty.

3.3 Narrative embedding and ontological uncertainty: the plasticity of the past

Ontological uncertainty prevents actors from envisioning the possible consequences of their actions, which will be mediated in part by interactions among agents, about and through artifacts, which currently do not exist in the actors' world – and actors will eventually express, interpret and evaluate these consequences in terms of attributions that they currently cannot even formulate. Thus, actors facing ontological uncertainty should not, and if they are even dimly aware of the ontological uncertainty in which they are immersed, *cannot* use the value of future consequences to generate appropriate action in the extended present. Narrative logic provides an alternative mode to generate such action, through its immanent link between character and denouement. Of course, this link is an essential element of *narrative* – not of the *world* itself. Events may spin out of control of a narrative,

[23] Certainly the *effects* of their actions can surprise them, particularly when the narrative embedding on which they are operating provides a poor representation of the actual context – this is an entirely different issue.

and the narrator may be forced to abandon it. But while the narrative is in place, the narrator – equipped with a sense of direction aligning him towards the denouement, and an understanding of his own character and that of the other actors with whom he is enmeshed – can continue to enact it, even if narrative canon forewarns him to expect all sorts of new obstacles in his path that make finding the right route a problem he must resolve moment by moment, "extended present" by "extended present", without a detailed road map for the future.

Of course, narrative logic is a local, not a global, solution to the problems posed by ontological uncertainty. Sometimes, events outstrip actors' capacity to interpret them consistently with the story they are currently telling about them. There will be periods in which actors just tread water to save themselves from drowning in an interaction stream, or just drift passively and helplessly with the swirl of events. In this situation, *narrative shifting – that is, re-embedding the current situation in a new narrative –* can serve as a kind of tow-boat to pull the actor out of the eddies and into a new current, fast flowing in what seems to be a desirable direction, and, at least for now, and as far as the actor can "see," free of treacherous sand-bars or counter-currents (see the next subsection for an example of such a transition). The capacity to move so quickly and to cancel the need to assimilate the old story with the new is a powerful tool for redirecting action in a world of rapid change. Even if there are no guarantees that the new story will lead actors where they thought they wanted to go, at least it keeps them moving for awhile, and there is no reason to suppose that there won't be a new story to guide them the next time they round a bend and find something they were totally unprepared to meet.

We were surprised at the frequency and extent of the narrative shifting that we encountered in our Echelon interviews. An informant would tell us about a new initiative in which Echelon had recently embarked, in partnership with a company whose competences perfectly complemented Echelon's and whose top managers were completely won over to the idea of distributed control or interoperability – but when we returned in three or six months, we would hear about the same events, this time embedded in a very different story. The new story rarely fit with the old one, as a tale of discovery and consequent disillusionment might. Rather, characters – including the Echelon informants themselves – had different *directedness* toward the relationship from the start; sometimes a new character would be present in the second story but not the first, whose role was precisely to subvert any possibility of achieving the transformations Echelon had envisioned, and who had been steering the other participants on a collision course from the outset in the revised version. Even more surprisingly, several stories about initiatives that had at one time seemed promising, but in the end led nowhere, were simply erased from the memory of the very informant who had been telling the story, perhaps over the course of months. On one occasion, an informant began to tell a story that seemed to resemble very closely a story we had heard from the same informant two years previously – even down to the identity of the principal other character in the story, a well-known computer networking company. When we asked how the new initiative differed from the previous, unsuccessful effort at collaboration with this company, we were met with a blank stare. However that other interaction stream had gotten recoded as a story, the resemblance was too faint for our informant even to recognize the similarity with the story now being told.

In retrospect, we should not have been surprised at the rapidity with which narratives, and hence action directions, changed. Most of us live in relatively stable worlds, where the things we do and the peoples and organizations with which we interact do not change much from day to day, month to month, even year to year. The attributions of identity we assign to others in our world are based on relatively long histories of interaction, which take place in familiar settings that provide us with many cues – cultural, physical and linguistic – about what is happening and what it means. Moreover, the transformations we seek to accomplish in the structure of our world tend to be relatively minor, keeping most of our physical, institutional and cognitive landscapes unchanged. None of these things are true in the work-life of Echelon people, at least for those whose job it is to find ways to bring about the major transformations of agent and artifact organization that will be necessary to realize a single control market system, centered on LonWorks distributed control, featuring interoperability down to the level of sensors and actuators. In this world, semantic and ontological uncertainty are huge and ever-present. Even the very words the actors must use to describe what they want to do – starting with control and interoperability – have meanings so different for different agents with whom Echelon must interact that mutual incomprehensibility lurks around every conversation. Moreover, how artifact systems are put together is embedded in agent role structures, in contract law, in shared and implicit attributions of artifact functionality, which may all differ substantially from one market system to another. Outsiders like the people from Echelon can only come to understand all these taken-for-granted aspects of market system reality slowly, peeling off layers of meaning and practice one by one through repeated interactions with insiders from these different worlds. To establish patterns of interaction that permit this kind of industrial anthropology is not easy. Echelon is a small company (even now, it has only around 200 employees), with a huge number of potential customers and partners in building the market system centered on LonWorks technology. Sometimes the ontological uncertainty all this implies is overwhelming:

In this kind of situation, an actor's "story" about his world is likely to change over time, sometimes rather quickly. Attributions of identity to the cast of characters in an interaction stream are mutable – too much is not only unknown at the beginning of a relationship, but even unimaginable. Echelon actors are almost all from Silicon Valley, and they inherit their narrative structures from this very particular milieu, far from the Midwest-based big control system producers like Honeywell and Johnson Controls, and even farther from European or Asian building contractors or controls companies. So their repertoire of narrative structures is frequently inadequate to represent the allowable plot transformations that their fellow actors are in the habit of enacting, and many of the interaction modalities that are taken for granted in Silicon Valley elicit responses from the other companies that seem inappropriate or puzzling to the Echelon actor-narrators. Other characters "take control" of the story, and the narrator has no choice but to search for another story that brings everything back in line – that is, that renders that part of the world once again, for another moment of the extended present, interpretable and thus open to action. What still does, even in retrospect, seem remarkable to us is the *plasticity of the past*: the facility with which one narrative replaces another when its predecessor reveals its failure to generate action for the narrator, and the ease with which the narrator adjusts action to the plot requirements of the new story.

Frequent narrative shifts, though, do not characterize all our Echelon informants. Some, from marketing and sales, have responsibilities that keep them operating within one particular market system – home automation or HVAC or factory control. Their job is to understand these systems and develop opportunities for LonWorks technology within them, so that they come to understand, if not quite from an insider's perspective, who are the various agents in their assigned zone of agent space, what they do, and how they think about the artifacts they design, produce, install and service. The stories from these informants are about slow progress, irregular but cumulative; about assimilating LonWorks technology into particular available niches in their respective zone of artifact space. At least before 1998, there was little role in their stories for interoperability, "control down to the sensor-actuator level," what some of their interlocutors in the big control companies called "Lontopia".

Another group of Echelon actors that have relatively stable stories are the engineers who design the hardware and software that constitute Echelon's product offering to customers in the LonWorks market system. Their stories are mainly about artifacts, as they are relatively insulated from direct contacts with outsiders, except when they work on a joint project with engineers from other companies. Clearly, the extended present is much longer for these two groups of Echelon actors than for those who are trying to deal with the bigger picture of the emerging LonWorks market system – and Echelon's identity within that changing world.

3.4 Narrative embedding in action: a story

This story takes place in the fall of 1996. By then, LonWorks technology had achieved a level of success in the HVAC market system, but very little in industrial control. Echelon's marketing efforts in the HVAC market had been two-pronged. On the one hand, Echelon sales and marketing worked hard to persuade the big control companies (Honeywell, Johnson Controls, Landis and Gyr, Siebe), to introduce LonWorks technology into parts of their product lines, on the grounds of dramatic reduction in time-to-market for new products and substantial reduction in manufacturing costs, even if these companies were unwilling to move towards real interoperability or to abandon their hierarchical control architecture for a more distributed one. At the same time, Echelon encouraged the smaller controls manufacturers to develop interoperable products based on LonWorks technology. For these companies, distributed controls and interoperability could provide a way better compete with the big providers, through advantages like lower initial installation cost, greater variety of products, lower maintenance costs through competitive bidding, and the ability to integrate other building systems such as lighting, security and fire safety systems.

While the HVAC strategy seemed to be working, Echelon's CEO and top management team were frustrated that things were not moving faster. A successful entrepreneur, the CEO had founded and served as CEO of ROLM, which introduced the first digital PBX and in a mere five years had wrested 1/3 of the PBX market from telecommunications giants AT&T and Northern Telecom, before agreeing to be acquired by IBM in 1984 (Lane and Maxfield, 1997). When he was feeling restless with the pace at which the LonWorks market system was growing, the CEO would talk about finding a way to "take control of our own destiny."

The major HVAC controls companies moved very carefully when introducing new technology into their product lines – they worried about many issues such as re-training of sales, installation, and maintenance personnel, and compatibility with installed equipment. While Echelon was making progress with them, it was very limited in its ability to speed up the process. On the other hand, it appeared that there were ways Echelon could accelerate the rate of progress in the other fork of the strategy – influencing the emergence of open, interoperable systems. In particular, it was clear that if the potential for multi-vendor, multi-function interoperable building systems were to be realized, a new type of agent would have to come into existence – a "LonWorks system integrator". These companies would design, install, and maintain interoperable systems using interoperable LonWorks products from many manufacturers, in contrast to the major HVAC controls companies with their proprietary product lines. Since the idea of interoperable systems was new, these "system integrators" did not exist – they would have to be recruited, and it wasn't at all clear where they would come from. There were several possibilities: entrepreneurs might start new companies to exploit the opportunity; existing companies that performed system integration in other market systems, such as information or telecommunication systems, might expand into this area; or small independent contractors specializing in custom building systems might be recruited. Echelon decided to launch a major initiative to identify, train, and support a network of system integrators.

In 1994, Echelon hired a new employee, AT, from a building contracting background, rather than from a Silicon Valley electronics company like almost all the other Echelon marketing and sales people. AT's first assignment was to build a training course for "LonWorks system integrators". Echelon top managers initially had in mind very large companies, like Olivetti (information systems) or Ameritech (telecommunications). In fact, Echelon had invited the CEO of Olivetti to present the keynote address at the autumn 1996 LonUser's meeting in Nice. Olivetti had a large clientele, particularly banks, for whom they designed and installed information systems, and the idea was that through LonWorks technology they might add facility management capabilities to their product offering. Just turning off computers and lights automatically when office occupants for day could produce serious cost savings for a typical Olivetti client. The situation with respect to Ameritech, an ex-Baby Bell, was similar, although their customer base was located in a huge number of households, for whom they installed telephones and were currently in the process of building up a large home security business. In his address at the Nice meeting, Echelon's CEO told the audience that he had recently talked with a top executive of an HVAC controls producer, who told him, "I wondered how long it would take you guys to discover the system integrators!"

AT, though, came from a different world, and the kind of company to which he gravitated as he began his work for Echelon looked very different from Olivetti or Ameritech, but quite similar to his ex-employer, an electrical contracting company. He began to work with a new kind of potential customer, the so-called "independent" controls contractors, who competed for medium-sized building control contracts with the big control companies' distributors. These contractors in general used control components from smaller manufacturers, which they customized with their own programming, or even used equipment from more than one manufacturer, writing gateway software themselves. The independent control contractors represented a level of the market system that had been below Echelon top management's radar screen: these companies didn't produce anything except one-off system software, they were typically quite small with annual revenues from \$5-\$30 million, they served clients in a relatively confined geographical area, and they did nuts-and-bolts system design and installation work.

In 1996, AT presented an idea for a new product with which non-Neuron-chip-equipped devices might be connected into a control system based on LonWorks technology.[24] Such a product would enable the independent controls contractors with whom AT was talking to bid more LonWorks jobs, since the product would allow them to add to their networks some equipment manufactured by companies that had not yet added LonWorks networking capability to their products. AT enlisted some allies from Echelon's engineering group, who were primarily attracted to the challenge of designing the product, and this group managed to interest the CEO in exploring the possibilities the new product might offer Echelon, in particular because of his interest in moving the markets towards interoperability. Echelon's CEO and its VP for Marketing decided to visit three of the independent controls contractors – AT's version of "system integrators" – with whom AT had begun to establish relationships.

The visits took place in early December 1996. They had a profound effect on Echelon's CEO. He recognized in the owner of one of these companies the counterpart of a group of people that had played a paramount role in the most important story of his business life, the successful entry of ROLM into the PBX market. When ROLM decided in 1974 to enter this market with the first digitally-switched computer-controlled PBX, it faced an uphill battle against the giant that then dominated the recently deregulated PBX market, ex-monopolist AT&T. ROLM did not have the resources to develop from scratch a distribution system able to sell, install and service PBX's throughout the entire US. Without some such system, there was no way to sell their product, no matter how much new functionality it might offer. What ROLM decided to do was to enlist a network of so-called "mom and pop" interconnect distributors, small regionally-based companies that customized and installed PBX systems manufactured by AT&T's much smaller competitors. These distributors were all fairly new to the PBX business, since they could only have entered it after the 1968 deregulation. Their problem was that the systems they could offer customers (manufactured by IT&T, Stromberg-Carlson, and other, smaller companies) offered no features not available with AT&T's systems, so they could only compete on cost, which reduced their margins to the vanishing point. ROLM's innovative system offered them a new lease on life, and those who decided to bet on the small Silicon Valley company and join ROLM's distribution network grew dramatically and prospered with the success of ROLM.

[24] See section 5 for an account of the genesis of this idea.

The CEO returned from his visit to the independent controls contractors and told the Echelon management team, many of whom were ex-ROLMans, that *these* “system integrators” could help do for Echelon what the interconnect distributors had done for ROLM. He recommended that Echelon develop a plan to institute a distribution system modeled on ROLM’s deals with their interconnect distributors. The system integrators would stimulate change in the market by offering the benefits of distributed, multi-vendor, interoperable building automation systems. If they were successful in competing against the major HVAC companies, then the majors would be forced to either make a commitment to embrace the concept of interoperable systems and move much more aggressively to implement products based on it, or face significant loss of market share as the system integrators captured the market with a superior solution. However it turned out, LonWorks technology would be the standard technology and Echelon would prosper.

Although the identification of the small control companies with the ROLM interconnect distributors was far from complete – especially since the major HVAC companies, now cast in the role of monopolists like AT&T, were already customers of Echelon – it offered an attractive basis for building a new narrative logic upon which Echelon could act to “take control” of its destiny, and it would have far-reaching implications for Echelon’s strategy and identity.

As the plan took shape, it became clear that the putative system integrators did not have the technical resources to implement truly distributed control systems; in order to displace the expensive central controllers, the new line of products, now called LonPoint® devices, would need to be much more than just hardware input-output devices; the devices would need to also implement many of the control algorithms normally programmed into the central controllers. [25] Thus in taking on the role of ROLM, Echelon would have to undergo a fundamental change in its own identity. Until then, Echelon had presented itself as a “technology provider,” a sort of benign Microsoft with the big control companies in the role of the computer manufacturers. Now, with its new identity inherited from the ROLM story, Echelon was going to enter the control business itself with the LonPoint product line. Inside Echelon, this identity shift came to be described as “moving up the food chain”.

Once the new story took shape, some new characters that had not been a part of the original ROLM story got recruited into it. The Echelon actors who adopted the new story began to try to cultivate a new potential ally, the so-called “big-iron” companies, like Carrier and York, who produced big HVAC components like chillers and air-handling units, but in general left their assembly into an end-user system to the large control companies like Honeywell. In the new story, the big-iron companies could embed the LonPoint devices under the skins of their components, providing substantial cost savings to the end-user, enhanced profits to the big-iron companies, and less dependence on the major controls companies.

Thus narrative logic carried the CEO from an identification between two kinds of people in two different contexts, to the transfer of an entire narrative structure from one of these contexts to the other. This transfer happened very rapidly, and it implied a change in strategic direction for Echelon. The denouement of the new story looked more advantageous to Echelon than what the previous story had seemed to offer. Just how that denouement would be achieved would be for the future to determine – in the extended present, the story demanded action, and Echelon responded.

One episode in particular illustrates just how decisive for action this narrative shift was. It was proposed that LonPoint devices should be sold *only* to independent control contractors who enrolled in an Echelon-sponsored “system integrator” program, with exclusivity by geographic region.[26] Clearly,

[25] See subsection 5.2 for details.

[26] This was in mid-December,1996. In October, at Nice, The exemplar “system integrator” was Olivetti; now it was M&E Sales, the Baltimore-area independent controls contractor that he had visited the first week in December and had identified

this idea followed from the identification of system integrators as a distribution channel, inspired by the ROLM-based narrative; the rationale was to strengthen the competitive stance of the system integrators against the proprietary systems providers. The assumption was that as the major controls companies decided to respond to competition from the distribution channel, they would develop their own versions of LonPoint devices rather than buy them from Echelon. But what if this assumption turned out to be wrong, and big HVAC customers wanted to acquire LonPoint devices? Should a company struggling to achieve profitability limit the revenues from a potentially hot new product, not to mention take on the difficulties implied by upsetting the big control companies, which they had long been assiduously cultivating? The intense discussions that followed were inextricably tied to the bigger issue of Echelon's identity, and competing narratives with very different attributions of identity to all the characters in the story played a decisive role in framing the rhetoric with which different Echelon actors tried to influence the outcome.

3.5 Cognition and communication

In developing our narrative theory of action, we have skirted around an issue that deserves further consideration: the relation between *cognitive* and *communicative* processes. To begin, consider the following epistemological issue. As we see it, there are only two kinds of sources of information about action in innovation contexts: actors' testimony, either direct (for example, through interviews) or indirect (through documents in which actors describe and explain what they do to others); or public data about the *results* of interaction, for example patent filings and awards, or published announcements of consortia or other joint projects. The latter kind of source tell us little or nothing about the processes at the individual actor level whereby these results are accomplished, which is what we are trying to address with our theory. The former can give us insight into these processes, but the sources themselves are the results of communicative action. So any inferences we make from them about cognition depends on how we think about the relation between cognitive and communicative processes.

For us, actors' *thinking* about innovation contexts is inseparable from actors' *talking* about them. In the kind of situation we described in the previous subsection, which is anything but routine, all action is interaction, and most action is discursive. In some of these conversations, like the CEO's with the independent controls contractors, the actors discover aspects of their world they didn't know about before. In others, with their closest colleagues, they make sense out of what they have discovered, modifying and rearranging their attributions about the entities and relations that compose their zones of agent-artifact space. The cognitive act of constructing the actor's representation of agent-artifact space is social, communicative – and the language in which it is carried out is the language of narrative. This does not imply that what actors say is what they think – that depends, as always, on who is talking to whom, with what communicative intent. It does imply, however, that the simplest assumption we can make, and in our view also the most plausible, is that the language in which they reflect about the contexts in which they act is the same as the language in which they engage in incessant discussion about these contexts – and that when they are speaking with colleagues whose attributions must be aligned with theirs if they are to engage successfully in joint action to achieve mutually desirable transformations, it would be very surprising if what they said, at least with respect to the attributions that mattered for that particular relationship, were much different from what they thought. When we analyze any particular conversation, of course we must take into account issues of communicative intent – but we may also assume that in certain conversations, what is said accurately represents the way actors think about the situation in which they are acting, and that the same thoughts that generate

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with the mom-and-pop PBX independent distributors. The Echelon system integrator program was to be targeted at M&E's, not Olivetti's.

the communicative acts whose traces we are analyzing also underlie the other actions that together compose the actors' contribution to the construction of the interaction streams in which they are immersed.

In our case, the managerial style of Echelon's CEO included keeping his Board members well informed about on-going Echelon initiatives, and he rarely hesitated in sharing bad as well as good news. We believe that in his communications to the Board the CEO is describing his real concerns and his ways of making sense out of Echelon's current situation. Some of our interviews with other Echelon employees also have this character, while in others there were other agendas on the table. For example, some of the interviewees seemed to be trying to use us as conduits for carrying their viewpoints to higher management. Others, though, seemed to welcome the opportunity to talk "in a more abstract way", as one subject put it, about the company, where it was going, and what they were doing to help get it there.

In the interviews, two kinds of stories emerged. The first had the character of the CEO's Board communications, reports on ongoing interaction streams – what was happening and what the interviewees told us they felt about it. We followed many overlapping interaction streams – some of which ended abruptly, others of which took unexpected turns for better or worse. It was in this context that we observed many instances of narrative shifting, as our subjects changed the stories in which they embedded events – without in general commenting on or, as far as we could observe, even noticing these changes. Tracking these interaction streams, and the various actors' interpretations of them, was like searching for the headwaters of the Nile: disappointing turns into unimportant tributaries, unexpected rapids to negotiate, sharp bends in the stream.

The other kind of story was retrospective, in which we would ask a subject to tell us about something that had already "finished", as far as the interviewee was concerned. Here the story spanned the whole Aristotelian gamut, beginning, middle and end. And usually something more – a moral tacked on. These stories were like floating down the Nile from Aswan to the sea – calm, straight, inevitable. These stories are very interesting, but in our opinion they give us little insight into what the participants were thinking as the stories were playing out. Not that these stories aren't very important for our theory – in fact, we think that their finished forms serve as carriers of narrative structure, ready to be transferred to newly encountered contexts for which they might provide the interpretative key – and, given how they turned out, to generate action possibilities to enact or avoid in the present. Hearing the first kind of story and discussing what actors were thinking of doing next led to our theory of narrative embedding and logic. On the other hand, that the second kind of story wraps a lesson in a narrative is no support for a theory of action in the extended present. In addition, it provides very dubious guidance to an analys about how what happened actually occurred.[27]

Thus, we believe that the Board communications and the ongoing interviews provide us with a basis to infer the role of narrative in structuring the way actors think about their contexts and their own actions in these contexts. As a result, we believe that narrative embedding and narrative logic are real phenomena in actors' extended present. Our conclusion that they are *causal* and not merely epiphenomenal follows from three further arguments. First, the assumption of causality provides coherence to a whole set of actions in a particular context, as we hope the story in the previous section illustrates. We can understand why the CEO was energized after the meeting with the potential system integrators, why his frustration over slow progress suddenly evaporated, and why in the span of only a

[27] Many authors in the business literature take a different point of view on this question. They draw lessons about the reasons for the success stories they report, on the basis of interviews with actors who tell their stories, retrospectively, as successes. This makes it easier to write "bullet points" giving managers' successful recipes for action, but in our opinion it doesn't get at the processes these managers actually have to use to confront ontological uncertainty. Though of course they may enlarge the managers' set of available narrative structures in which they might (temporarily) embed some new context.

week or two he began to push with confident aggressiveness a whole new approach to the relationship with system integrators and a modified identity for Echelon. Moreover, we can see the common basis for the particular set of actions he was pushing, which otherwise would be difficult to account for.

The second argument is that our actors too seemed to believe that narrative logic was causal, in that when arguing about what constituted appropriate action in a particular situation, they frequently advanced their position by means of narrative logic and they defended their position by attacking their opponent's *narrative* logic. For example, the CEO repeatedly used the ROLM story to convince the top management in Echelon of the rationale for "moving up the food chain" and for indications of how to accomplish the move. Others in the company were not initially convinced that Echelon should "move up the food chain." They pointed out some real differences between the independent controls contractors and the mom-and-pop interconnect distributors: their relations with existing equipment suppliers, how long they'd been in the business, their growth expectations

One can object to this argument, on the grounds that actors' beliefs about causality can be wrong. Certainly, but when it comes to believing that their own actions are caused by something, if that belief is not contraindicated by their experience and if we, as outsiders, don't find the belief contraindicated by *our* observations of what the actors are doing, it is hard to see why we shouldn't believe it too, if we want to make sense of their actions. That is, it is clear that we can understand the rhetorical force of the arguments for and against moving up the food chain, if we assign a causal role to narrative logic. If not, we have to say that the rhetorical force derives only from the fact that both must be acting as though they assign a causal role to narrative logic for themselves *and* for each other. If in the end, everyone acts as though they believe that they and everyone else assign a causal role to narrative logic, in what sense could we argue that it doesn't *have* a causal role?

The third argument is a negative one: we couldn't think of any other alternatives that would explain what we were observing. Moreover, given the total lack of explanatory power of a rational choice, routine or random-search based alternative, we have the impression that no one else has any serious alternatives to offer either.

4. Ontological uncertainty and generative relationships

The most important *cognitive* process in innovation is the generation of new attributions, and the most important communication processes involve the aligning of attributions among agents. Frequently, innovation begins with a new attribution of functionality – an idea for a kind of activity in which people may wish to engage that can be realized by means of an artifact.[28] Moreover, virtually all *constructive* innovation processes require new attributions of identity for the new entities in agent-artifact space that these processes generate. Since identity is relational, the construction of new entities that become incorporated in patterns of activity with previously existing entities generally requires modifications in the attributions of identity for these entities as well.

In a previous paper (Lane and Maxfield, 1997), we argued that new attributions arise in the context of a particular kind of relationship among agents, which we called *generative*. While ontological uncertainty makes it impossible to predict in detail what sorts of new attributions a relationship may generate, it is possible to assess the *generative potential* of a relationship. This potential depends on five characteristics of the agents in the relationship and their modes of interaction with one another, and agents may not only infer the degree of these characteristics through their interactions, but may also act

[28] Artifacts may be physical or informational; in particular, both goods and services may be viewed as artifacts. An artifact is anything produced by human beings from natural resources and artifacts, to be used by human beings to carry out some desired activity.

in such a way to increase the relationship's generative potential: aligned directedness, heterogeneity, mutual directedness, appropriate permissions, and action opportunities.[29]

In zones of agent-artifact space that are undergoing rapid change, identities change, and agents need to track these changes carefully in their attributions of identity of the significant agents and artifacts in their world. The process of monitoring and interpreting identities requires discourse with others, since any agent has only a partial and restricted view of what others do – never mind how they interpret what they are doing. This discourse is channeled through the agents' informational and interpretative social networks.[30] While Granovetter's famous idea that informational networks are primarily composed of weak ties may have merit even in the innovation context, *interpretative* networks generally require the strong ties that characterize on-going generative relationships. The relationships in question may be among actors who work for the same firm, groups of actors from more than one organization engaged in joint projects, or agents working together under the auspices of a market system scaffolding structure (see section 5). The important point is that in generative relationships, agents have *aligned directedness* – that is, their interactions are focused around achieving similar transformations in the same zone of agent-artifact space – and they are characterized by significant *heterogeneity*. Unlike social actors who may prefer the company of like-minded others, innovative agents have to seek out and build strong relationships with others that differ substantially from them in some important respects – even if they hope to construct eventually a set of attributions about artifact meaning and agent roles sufficiently aligned to support a stable market system around the artifact family they are trying to bring into being.

Whatever the kind of heterogeneity that attracts the agents into working together – differences in competence, in position within social or economic networks, in access to particular resources – these agents are bound to have different attributions about important artifacts and agents in their common world, differences that reflect the heterogeneity of their past experiences. Attributions are not directly observable – even less so than the other sources of heterogeneity mentioned above. As agents begin to interact to establish patterns of joint action, attributional differences among them may surface – typically, in the form of utterances that cannot be coherently interpreted from the point of view of the attributions the listener has assigned to the agents or artifacts to which the utterance refers.

Agents may respond in several different ways to their discovery of attributional difference. They might confuse their own attributions with "reality" and decide that the other is either ignorant or less intelligent – a reaction that can be encouraged by attributions about social or intellectual differences between discourse participants. For example, Silicon Valley entrepreneurs and engineers, especially before the NASDAQ crash in 2000, tend to believe that their business and technological visions are superior to those in more conservative industries and locations; or these others may feel that Silicon Valley entrepreneurs and engineers are too arrogant to see how little they understand about the realities of business in particular, non-Silicon Valley-based market systems. This mode of reacting to differences undermines *mutual directedness*, one of the determining characteristics of generative potential, and typically prevents the relationship from further development, never mind generating anything.

A second reaction mode is to step carefully around any attributional differences that may surface. This reaction is more politic and may permit the relationship to continue, and it may even enhance the generative potential of the relationship if a particular attributional difference is so tied to the identity of one or the other agent that its exploration could only lead to the termination of the relationship. However, if all differences must be handled in this way, the participants in the relationship do not have

[29] For definitions and explanations, see Lane and Maxfield (1997) and below in this section.
[30] See Lane et al. (1996).

the appropriate *permissions structures* (what they can say to whom, about what, in which illocutionary mode) to provide generative potential to the relationship.

If the relationship really has generative potential, then participants can respond to attributional differences when they surface by exploring them, through extended discourse. That is, participants can recognize and attempt to resolve their mutual discoveries of semantic uncertainty. As discourse expands around the discovered difference, semantic uncertainty typically increases for all participants, as more and more of their attributions are linked to those for which the differences were first discovered – and differences among these too become revealed. What such a process may lead to is cascades of change in each participant's attribution set – that is, their representations of the structure of agent-artifact space. It is this process that leads to new attributions. Opening up attributions for discussion generally is not resolved through anything as simple as replacement (that is, accepting another's attribution in place of one's own) or combination (that is, merging through Boolean operations that put together one's own attributions with those of another). Rather, from what others reveal about their attributions, one may realize new *dimensions* for evaluating aspects of identity – and these new dimensions may lead to new possibilities for relations among different attributions, which imply shifts in the attributions themselves. But given the differences in starting points, and the difference in interpretations of the added dimensions, there is no reason to think that attributions of different agents need come "closer together" through this process, never mind come into alignment.

We now turn to a story that illustrates the two kinds of processes discussed above: how agents facing ontological uncertainty can enter into and nurture relationships with generative potential; and how generative potential may be realized through the discovery of semantic uncertainty, whose exploration may lead to new attributions that may then be instantiated in new kinds of artifacts or agents. The story illustrates how ontological and semantic uncertainty lead to more ontological and semantic uncertainty, as efforts to resolve them also uncover further entities, relations and concepts that must be interpreted in their turn. The locus of these transformations can shift from one set of actors to another, from one generative relationship to another. The story is long, because the processes it is intended to illustrate are subtle and highly context dependent, but its moral is simple: novelty often arises from relationships and context, not only in flashes of inspiration in individual brains.[31]

By 1994, many people in Echelon were coming to feel that converting the major controls manufacturers to the ideas of a standardized communications protocol and interoperability was, in the words of one of them, like "pushing on a rope". Since the advantages of interoperability accrued to end-users, Echelon managers decided to figure out ways to win them over to their cause, resulting in "demand-pull" on the controls companies from their customers. They established an End-User Program, a strategic move replete with ontological uncertainty. The category "end-users" included manufacturing companies and building owners and managers – a huge number of agents, geographically dispersed and culturally very heterogeneous. How to reach them? The first move was to try to raise their consciousness about what distributed control might do for them, through a series of seminars, but given the magnitude of such a task, it was mainly organized and carried out by Motorola, one of Echelon's two semiconductor partners, who manufactured Neuron chips. Motorola, of course, had a much larger sales force than Echelon, with many more resources that could be dedicated to this sort of market-building effort. It turned out, though, that from Echelon's point of view this approach ran up against two problems. The first was that Motorola's salesmen were, naturally enough, chip-, not system-, oriented, and so it began to appear to Echelon people that they were not particularly effective at communicating the advantages of system-level features like interoperability, which were crucial to Echelon's directedness. The second problem was a practical one: even if building or factory owners

[31] The story is based upon repeated interviews with participants, carried out from February 1996 through July 1997, as well as documents supplied to us by some of the people we interviewed.

did become enthusiastic about the possibilities of distributed control, to whom could they turn to design and install distributed control systems? As described earlier, to deal with this issue Echelon decided to find potential system integrators and train them, so that they could offer to end-users control systems based on LonWorks technology that were competitive with those of the big control companies.

While top Echelon managers initially did not have a clear idea about what kinds of companies these system integrators might be, it was clear that the people who would do the design and installation work on one-off systems were not likely to be computer whizzes or up on the latest in network science. To convince such people to commit to LonWorks technology and to figure out how to teach them to use it, it would be a good idea to find someone who knew a bit about their world and thought like they did. An Echelon salesman mentioned that he had heard about someone who worked for a big electrical contractor, had done good work on a high-tech Disney studios project and was looking around for a new job, and Echelon ended up hiring him.

AT, the new employee, went to work with a will, learning about LonWorks technology and Echelon products by reading the technical literature produced by Echelon's product marketing group and attending the introductory course Echelon offered to engineers who planned to design control systems for particular artifacts, like automated bar-tenders for casinos, car-wash machines, or semiconductor fabrication vacuum pumps, all early successful products based on LonWorks technology. He also sought out potential recruits for the course he planned to develop by visiting controls contractors around the US. In part because of his own buildings background and in part because of differences in the structures of the different controls market systems, all of the companies AT identified were in the HVAC business. One of these, with whom he began to develop a working relationship, was TEC Systems, a Long Island HVAC controls contractor that was the largest "independent" (that is, not a subsidiary or affiliate of one of the big three HVAC control companies, Honeywell, Johnson Controls, or Landis & Staefe) in the New York area, with about $30-40 million in annual revenues.

The LonPoint product we mentioned in section 4.3 was conceived and developed in the context of the relationship between Echelon and TEC. For the rest of this section, we relate three episodes in the story of the genesis of LonPoint productss. The first and last of them have to do with generative relationships between Echelon and TEC, featuring different actors and different aspects of LonPoint technology. The second takes place mainly within Echelon, though TEC and a few other system integrators that AT recruited play an important role here too.

Episode 1: LM and AT make a surprising discovery This episode takes place late one afternoon in early December, 1995. LM is a partner in TEC Systems, in charge of sales and marketing. He and AT have spent the whole afternoon at TEC, discussing a problem LM is having with LonWorks technology. He has been hoping to bid on a big JFK airport job, using LonWorks technology to integrate the products from multiple suppliers, but the more he tries to put together a workable design, the more frustrated he becomes, because there simply are not enough kinds of components – built-up air handlers, fans, reheat coils – that are equipped by their manufacturers to act as nodes in a LonWorks system. The problem is, what can LM and AT do about this situation? AT is about to ask a question, the answer to which will take him and LM into the TEC lab to pull apart a bunch of HVAC components there. What they will find, and what they decide to do about it, will be the first step towards LonPoint products. But before we go into that part of the story, let's look a little more closely at LM and AT, their relationship – and those determinants of generative potential we mentioned earlier.

AT As we have already seen, AT was not a typical Echelon employee. Because of his background in the electrical contracting business, he realized that the Echelon technical and product marketing literature were targeted to a very different audience and a great deal of work would be required to recast them into a form appropriate for a system integrator. Further, he realized that there were insufficient tools available to help system integrators configure and install systems. When he attended the introductory LonWorks programming course, he realized it was targeted to product developers, not to systems designers and installers. He quickly realized that the kind of system integrators with whom he was familiar would need a very different course, which he proceeded to develop. The first course was held in August 1995, and in the first year every course was sold out and about 120 people, including LM, had received training.

LM LM graduated with a degree in mechanical engineering in1983 and went to work almost immediately in the building controls industry around New York. In the early 70's, the three largest control companies dominated the market, making healthy profits. The energy crisis shook things up. New manufacturers brought in microprocessor technology, mostly simple things like clocks that turned off air conditioning 15 minutes per hour. In the '74-'78 period, some of these manufacturers were, according to LM, just "snake-oil salesmen," some legitimate; all were responding to the dramatic new increases in energy costs, which in NY had risen by 5-10% almost overnight. Some of these companies went under, others endured. In response to these new manufacturers, independent contractors like TEC got created. Many of the founders of these contracting companies used to work for the big three controls companies. They encountered the new manufacturers and their products at trade shows and decided to go into business for themselves, installing the new systems. The new independent contractors emphasized energy management. TEC, an acronym for Total Energy Control, was founded in 1981. It was not affiliated with any manufacturer. However, it found the learning curve for any one company's products is steep, so it fell into using primarily one manufacturer, American Automatrix, one of the post-energy crisis controls companies. TEC came to be perceived as an American Automatrix branch office.

The independents could bid 50-75% under Honeywell and Johnson, so they won contracts mostly on a price basis. From '84-'89, they won around 25% of the contracts in the NY area, giving them about 10% market share. The biggest of them did about $2.5 million in annual revenues, most much less. They would win jobs directly with end-users (that is, owners – or maybe a plant manager, told to control energy costs), mostly small projects. As a typical mode of operation, a salesman would come into a project, diagnose feasibility for energy savings, make a proposal. The big control companies were still primarily using pneumatic, rather than electronic controls, so the microprocessor-based business was new for them. In functionality, though, they caught up with the newer manufacturers by the mid-80's; they lost out only on price.

In 1990, the economy took off, and energy management cooled off. So the independents changed their emphasis to "control" – in particular, control of comfort in the workspace: if lights were too bright, or thermoregulation or air quality poor, workers weren't productive. They started making their pitch to human resources people, urging them to give more control to users in their local environments. HVAC equipment was changing too. The large central systems were being distributed downwards, and so control requirements were increasing: when there was one big fan for a building, someone could spend all day tweaking it, but when there was a different air handler on each floor of a building, that was no longer practical, so more automatic, microprocessor-based control, was necessary. Moreover, as the number of new construction projects grew, independent contractors wanted to move from retrofitting to new construction, but that brought new problems for them: unions, for example, as well as more requirements for financial strength.

As the independents changed their way of doing business, they competed more directly with the big three – and since the independents could still undercut the big three on prices, the big three's branch offices responded. They tried to get their own products written into the specifications prepared by consulting engineers, who often didn't know much about controls. At first this succeeded, but then owners began to balk as they began to understand the price implications. The independents counter-attacked by bidding on contracts designed to exclude them: they'd win on price and then aggressively work around the constraints in the contract they couldn't meet. The boom in building in this period helped this strategy work, and in the process they managed to convince some consulting engineers that they could deliver good systems as well as the big three.

So the independents were growing. TEC was getting about 30% of the jobs it bid on. By '93, construction managers and mechanical contractors liked TEC, who had never defaulted on a job. When the building boom stalled, competition intensified. A lot of independents at this time just scaled back, thinking why fight? We've made a lot of money, let's just retreat to the niches available to us. TEC fought back, but had great difficulties winning contracts. This was the situation when LM joined TEC in 1993, as head of sales and marketing.

In contrast to the independents, the big three's branch offices didn't work as hard at developing long-lasting relationships with their customers. They were not very responsive to product problems, and their pricing for maintenance and repairs was high. But with the pickup in competition from the independents, they began to change; they solved some hardware design problems and lowered prices. With the downturn in business in '93, and the black-eye that independents in general were getting from the failures of some of them, suddenly in '93 and '94 TEC couldn't get new business. When he came into the company, LM initially thought that the problem was due to marketing and promotion failures. He took initiatives like trying to work with engineering firms to get his products written into specs, changing the company logo, getting involved with industry functions like seminars and charity events, and publishing case studies. These initiatives had only minor effects. So he decided that the problem was more fundamental: TEC was no longer positively differentiated from the competition.

LM looked around for something that would give TEC an edge. A friend, who worked for the largest NY general contractor, had been approached by a Motorola salesman pushing LonWorks technology, and the friend agreed to host a meeting in June 1995, to which he invited numerous controls companies, including TEC. After listening to people from Motorola and Echelon describe the merits of LonWorks technology, LM thought that it might provide the angle that he was looking for: TEC could be a truly independent controls contractor, integrating products made by lots of different manufacturers. He believed the distributed controls would make possible significant cost savings. Having the communication protocol embedded in silicon made sense to him. Later LM documented the savings on panel fabrication and wiring costs, for a hypothetical job. They were substantial, on the order of 30%. He passed on his calculations to AT, who gave them to Echelon's marketing people, and both made great use of them in speeches and discussions throughout 1995 and 1996.

From June to November, LM investigated the availability of products based on LonWorks technology, and attended AT's system integrator course. He concluded that while there would eventually be many suitable products on the market, he was concerned about whether the timing was right for his firm to make a major commitment to LonWorks technology. The currently available products did not offer a sufficiently wide range of functionality; there was a wider selection of products from European manufacturers, but these were not certified to U.S. product safety standards by Underwriters Laboratory and other agencies. Nevertheless he assigned a TEC engineer to test the products that were available, and TEC became a certified LonWorks technology System Integrator. In the fall of 1995, LM was asked to give a presentation on LonWorks technology to the national meeting of ASHRAE, the premier HVAC trade association. With LonWorks technology, LM found, TEC could get valuable visibility – whether or not it was actually ready to install complete LonWorks systems. So by the time of the conversation with AT, LM was convinced that LonWorks technology was important for TEC's present and future, but felt that it would be while before it could be the basis of all of their system solutions for customers.

Generative potential of the AT-LM relationship Between AT and LM, there was plenty of mutual directedness. In addition, their permission structures were such that they could talk about virtually anything having to do with HVAC, controls and LonWorks technology. AT's willingness to help LM prepare bids for LonWorks systems, like the JFK job, provided them with action opportunities.

They were also aligned in their directedness to transform the HVAC controls market system in such a way as to provide significantly more opportunities for independent system integrators, by moving towards the acceptance of LonWorks multi-vendor systems. Multi-vendor systems liberate end-users from the change-and-maintenance lock-in to a single controls supplier, thus providing a lot of new possibilities – in design, installation, retrofitting, and maintenance – for the independent system integrators. Multi-vendor systems, though, do not necessarily imply "plug-and-play" interoperability. In fact, writing special gateway software to connect proprietary subsystems to LonWorks networks could be a profitable activity for independent system integrators with the necessary technical competence, like TEC. And there is a long way from multi-vendor systems to distributing control down to the sensor-actuator level.

Thus, the directedness that aligned AT and LM was not identical to the directedness of Echelon's top managers and product marketing group. By 1996, Echelon's management was fully committed to move the market towards interoperability and distributed control, which would be enabled by the LNS® network operating system that Echelon's engineering team was developing. The LNS operating system would provide an open framework for other manufacturers to design interoperable products that could be easily integrated into highly functional multi-vendor systems. For a variety of reasons, not the least their interpretation of the Microsoft story in personal computing, they believed that owning the operating system was the key to control of the control networks world. On the other hand, the focus on interoperability, distributed control and the LNS operating system was not central to AT – he was primarily oriented to his own particular task, finding likely candidates for LonWorks System Integrators and getting them to bid projects with LonWorks content. If he could find a way to quickly satisfy LM and others like him, LonWorks technology could accelerate its penetration of the market much sooner than waiting for the completion of LNS operating system and the time delay from its introduction until manufacturers embraced it and developed products based on it.

The only determinant of generative potential for which the AT-LM relationship did not achieve a particularly high score was heterogeneity. They tended to think alike about the HVAC world, so far as AT understood it. LM certainly knew that world better, and this alone introduced an element of attributional heterogeneity, as AT had a lot to learn and he felt comfortable enough with LM to ask about whatever was on his mind, which as we will see in a moment turned out to be important, when he asked LM a question that conventional wisdom in the HVAC world prevented LM from asking himself. LM and AT were heterogeneous in another sense: AT may not have had the most sophisticated understanding possible of LonWorks technology, but he did know more about it than LM – and, more important, he had relatively easy access to the people who understood it better than anyone else in the world. These two sources of heterogeneity – differential knowledge and access – turned out to be sufficient, together with the high levels of all the other determinants, to make their relationship not only *potentially* but *actually* generative.

An idea for a new product If there weren't enough LonWorks products to bid the JFK project, what then? AT had an idea: maybe there might be a way to "trick" a component into joining a LonWorks network by associating with it an external LonWorks node that could communicate with it in its own language. Then that LonWorks node could carry messages to and from the component to all the rest of the devices and components on the network, so the component would be a de facto member of the network!

So AT asked LM a question, "What kinds of signals do HVAC sensors and actuators respond to?" Immediately LM responded with that piece of HVAC conventional wisdom we mentioned above: "There's no standardization in HVAC; every device by every manufacturer can have a different kind of signal to which it responds." AT came from the relatively standardized electrical contracting business, and he refused to believe LM's response – at which point they repaired to the TEC lab and started tearing apart available components to figure out just what sort of input/output signals were used in real devices. Sure enough, they found that conventional wisdom was correct at the level of proprietary communication protocols between subsystems– but not at the level of the electrical signals used by the sensors and actuators themselves. They found only four kinds of input-output (I/O) signaling systems in all the components they checked. So if they could have one LonWorks node that could sense electrical inputs from an attached device and send communication messages to other nodes on the network, and another that could receive messages from nodes on the network and provide the appropriate electrical signals as output, then they could attach these nodes to any HVAC components – and the components could become part of the LonWorks network. Their idea was simple: if the component wasn't already equipped with a LonWorks node inside, you could just attach it to an external node that could translate between the LonWorks communication protocol and the electrical signals that were meaningful to the component, and the component would then become a functioning part of the network. AT decided to take this idea back to Echelon.

Episode 2: A mixed reaction Upon his return to Palo Alto, AT sought out Echelon engineer whom he had known from church choir days in Minneapolis. In early February 1996, AT, with help from this engineer and others, drafted a proposal for a new Echelon product, Enhanced Control Modules (ECM). The proposal argued that the new ECM product could accelerate penetration of LonWorks technology into the HVAC market, by empowering system integrators to compete effectively with the proprietary systems of the major control companies over the whole gamut of HVAC projects, including all sizes of retrofits as well as new constructions.

Echelon's chief technology architect enthusiastically embraced the ECM idea when it was presented it to him. He had designed the LNS operating system and was shepherding it through development, but he knew that it would take some time for the controls industry to understand and embrace the benefits of truly distributed control systems that the LNS operating system enabled. The ECM product could be developed rather quickly and was a product that everyone could understand and end-users and system integrators could appreciate, and would demonstrate the benefits of distributed systems, thus stimulating other manufacturers to get on the bandwagon.

Initially, the marketing group was not favorable to the ECM idea. They were concerned about two aspects of the proposal. First, there were already similar devices (called "I/O modules") on the market, manufactured by Echelon customers including Weidmuller and Action Instruments. How, they asked, did ECM differ from these products? Without a clear differentiation, marketing would be very reluctant to compete with Echelon customers. Second, the ECM proposal did not specify whether and how ECM would relate to the LNS operating system, and marketing wanted the latter to be the heart of Echelon's product line. Underlying both these concerns was a key question: just what functionality would ECM provide, beyond the purely communicative role that AT and LM had envisioned? In particular, what sort of software issues would have to be solved to *run* a control system with ECM nodes? If the LNS operating system were to be the heart of Echelon's HVAC solution, then that solution would have to be based upon apeer-to-peer control architecture. If that were to be so, what kinds of control algorithms – currently programmed in the central controller in hierarchical systems - would ECMs have to implement, and how might they do it?

The question of whether or not to proceed with the development of ECM was discussed at length at an off-site retreat of top management, and it was decided to proceed with a project to resolve the questions and develop the product. The project team consisted of members of the engineering and product marketing groups, as well as AT. The team asked AT to assemble a group of system integrators with whom they could discuss the product concepts; development was underway in March, guided by the discussions that the team had with the five system integrators AT invited, including of course TEC and M&E Sales,.

The product plans and prototypes that emerged by September looked quite different – and quite a bit more sophisticated – than what AT and LM had imagined the previous December. Marketing's two concerns had been more than satisfied. Both the hardware and software of the new products, now called LonPoint devices, differentiated them clearly from any other products currently on the market, and the software in the new modules was integrated with the LNS operating system. Some of the design innovations were about hardware features. For example, the team had learned that electrical contractors handled electrical power connections for HVAC equipment, while controls contractors installed and commissioned the electronics. So they designed a box in two parts – one installed by the electricians, the other containing the electronics that could be slipped in later, already programmed, by the controls people. Several other such innovative hardware features tailored the boxes for efficiency of installation and use.

LonPoint software posed much more complicated issues. As the team interacted with the system integrators, they came to realize that the set of functional capabilities required to solve all possible system problems was quite large, and that it would take a long time to do them all. So the goal for the initial product offering became "100% of 80%" – that is, with LonPoint devices and already existing LonWorks components, system integrators should be able to solve 100% of the problems they would encounter in 80% of all HVAC projects. And it became clear that they could not anticipate all the functionality that might be needed in the future, so the LonPoint modules would have to be programmable by users. But how – by means of a field compiler, or an interpreter inside the Neuron chip? And how to do everything in such a way that problems were not only "in principle" solvable, but to ensure that tools existed to enable the system integrator technicians, who did not have degrees in computer science, to solve them?

By December 1996, top management and the product team are fully committed and in high gear developing the LonPoint product line. Nevertheless, there are differences of opinion about the level of impact LonPoint devices will have on Echelon's future. Some, including the CEO, are very positive. They see LonPoint devices and the system integrators as the keys to moving HVAC towards distributed control and interoperability. The chief architect believes that LM and AT have underestimated the potential savings that can be realized with them – because their estimates were based on wiring and installation costs, while the real advantage of LonPoint devices may be through the elimination of costly controllers. Others are less sanguine: some are concerned about whether the system integrators will be able to adequately exploit the opportunities; for example, it appears that LonPoint devices will be most cost effective for very large systems, but the independent system integrators have heretofore rarely won these contracts. Others are worried about how the major controls customers will react to Echelon "moving up the food chain", making the independents more competitive.

Episode 3: 590 Madison Avenue, NYC The fifty story IBM building on this site is the scene of two important episodes in the LonPoint product story. The first happens in the fall of 1996. TEC has installed an HVAC system in the building, based on the Automatrix product line, that is as distributed as control systems get in 1996, and they want to show the Echelon people how it works. So the members of the LonPoint project team go to NY to look it over. There is an Automatrix Sage controller every two floors, and two larger work-station controllers supervising the system. TEC's custom program for "bringing the building up" is 40,000 lines of code. The engineers realize that HVAC control is a lot more complicated than it seemed from Palo Alto! They realize that they will have to have enough functionality in LonPoints software to substitute for all these Sages and work-stations, if they are really to move the market towards Echelon's idea of fully distributed control. And, sophisticated as they finds the TEC engineers to be, they know can't expect to find people in most system integrator's employ who will be competent programmers – the LonPoint devices, they become convinced, must be "programmed" mainly by setting parameter values.

The TEC engineers are very helpful. They carefully explain their system's architecture, give the Echelon team blueprints describing the system in detail, discuss the harder feedback control loops in the system and how they went about implementing them. They also take the Echelon team to Brooklyn College, to see a retrofit job. "A retrofit," one team member told us, "is like a heart transplant. Overnight you have to cut-over from one system to the other, so there's heat in the building in the morning – pipes hissing, compressors banging, a lot of ad hoc adjustments to do, very different from an intellectual appreciation of the problem. We're not selling tinker toys here—people have to go to basement of Brooklyn College, bring up a building and make it stick—you can't leave a lot of things as exercises for the student." A month after the NY visit, he is confident that "by now, we've figured out what we don't know."

In the months following the visit to 590 Madison, the team defines many new features into the LonPoint product family. There is a installation tool, LonMaker™ for Windows, that is integrated with the LNS network operating system with an easy-to-use graphics interface; thus, the LonPoint system is inextricably tied now to Echelon's operating system. It turned out that a purely *local* messaging system would not be adequate to give all the functionality that modern HVAC systems deliver, and so there is a LonPoint scheduler module, which provides a system-wide clock, capable of coordinating operating mode changes throughout an entire HVAC system, such as "night", "weekday", and "weekend". In addition, another LonPoint module can capture time series of data points from multiple network components, and upload this information to a pc, which can supply trending and other statistical services to users. And there is a new concept, the "plug-in," a piece of software written for any LonWorks component, which makes it easy for the system integrator working with LonMaker for Windows to configure the component and put it into the LonWorks control network.

All these additional elements in the LonPoint product family have introduced delays in the product schedule. In September 1997, a three-day meeting for people from 5 system integrator companies including TEC, originally conceived as a training course for alpha- and beta-testers of the LonPoint system, takes place, even though the LonPoint products aren't ready. The Echelon team demonstrates prototypes and describes current plans for finishing the products – and, most importantly, asks for comments from the other participants. The system integrators understand that they have an additional opportunity to influence the final shape of the LonPoint products, and they deluge the Echelon team with suggestions and comments: added capabilities to the LonPoint input/output interfaces (24 volt relay output); added math functionality (averaging many temperature variables, optimal start sequences); performance problems (20 seconds after dragging and dropping a device type until the configuration plug-in is loaded is too long a wait); security features (multiple people need access to the design schematic, but not all should be able to change the drawing); how information is displayed (the need to see a data value next to the object associated with it, not in a different window). Probably most of these items had been thought of by the Echelon team, but they would have been a small subset of long unprioritized lists of possible enhancements, so the benefit to Echelon came from understanding the *relative* benefits as perceived by the user. By the time the products are ready to ship in the spring of 1998, many of these suggestions, in one form or another, have been incorporated into the functionality of the LonPoint artifacts.

The second visit to 590 Madison takes place in early 1998. This time, the Echelon engineers, with the help of a crew from TEC, will take one of the air-handlers in 590 Madison off its centralized Automatrix controller, and build up a control subsystem for it consisting only of LonPoint devices. This is the alpha-test for the LonPoint system. The installation works. It is the first time an HVAC feedback control loop has been implemented with an entirely peer-to-peer control architecture.

Shortly after the installation, a thunderstorm causes a several-minute power outage throughout the building. When power is restored, the maintenance people have to scurry around to reset every Sage controller in the building. The LonPoint subsystem, in contrast, resumes normal service with no intervention.

5. Scaffolding structures and ontological uncertainty

In this section, we move up to the largest space- and time-scales we consider in this paper. The setting in agent space for our discussion is the *market system*, which we define in subsection 5.1. The structure of a market system is characterized by two kinds of organization: competence networks, which carry out market system functionality; and scaffolding structures, which provide the framework for constructing and reconstructing competence networks. Market systems are characterized by a tension between maintaining sufficient stability to sustain markets, and generating the steady stream of new artifacts that are one of the principal means through which market system participants augment their own positions *within* the market system and the market system as a whole secures its position in agent space. Scaffolding structures provide the space, opportunities and means for keeping this tension "in control." In particular, they are the principal locus where agents in the market system collectively confront ontological uncertainty. Subsection 5.2 describes how market system agents seek to segregate within scaffolding structures the processes through which new kinds of entities are admitted into the market system, and to channel these processes so that enough new entities are generated to maintain or even expand the market system – but not so many, or so novel, that they rupture it. Subsection 5.3 connects the theory of scaffolding structures with our theory of generative relationships.

5.1 Market systems and scaffolding structures

The *market* is an entity defined formally by economists and discussed informally by journalists, politicians and just about everyone else. It is a locus of impersonal exchange activities, where agents buy and sell products with defined characteristics, at prices that, according to standard economic theory, reflect supply-and-demand induced equilibria. Economic theory accords these prices the role of principal communication medium between agents, who use the information prices convey to drive their actions. Relationships between agents do not count for much in the market. What matters is how each agent separately values each artifact, values that the market then aggregates into prices. Frequently, in popular narratives about developments taking place in business and the economy, the market is assigned a central causal role.

Just as human beings cannot successfully carry on a conversation without a large, learned and culturally-specific set of conventions – for turn-taking, eye contact and facial expression, tone and tropes, not to mention meaning for words and phrases – so markets could not possibly function without *their* conventions. Market conventions include

- aligned attributions among participating agents about artifact functionalities and relevant properties of artifacts that affects how well they fulfill their functionalities;
- agent role structures – categorization schema that allow agents to know what sorts of agents participate in which kinds of interaction around which artifacts;
- modes of transacting – how prices are determined, what to expect from each agent participating in to a transaction and from artifacts exchanged or operations carried out upon or with them, what to do when expectations are not met.

Some of these conventions are explicit, some implicit; some are specific to particular markets (delimited geographically, culturally or by artifact), some are shared widely across markets. Together, they provide a stable cognitive and institutional backdrop without which a market could not possibly exist.

Of course, the stability of these conventions is not absolute, since a steady stream of new kinds of artifacts flow into "the market" every day – without in general generating so much confusion that existing markets collapse like the tower of Babel. Sometimes cascades of change *do* propagate through agent-artifact and attributional spaces – Schumpeterian gales of creative destruction. Just as obviously, these cascades are generally at some point damped out, new conventions stabilized, new markets established. Where do market conventions come from? On what time- and space-scales, and *how*, do they manage to be sufficiently stable to sustain markets – and sufficiently robust to incorporate new artifacts with new functionalities?

To get at these questions, we begin by defining a concept we have already used informally – the concept of a *market system*. A market system is a set of *agents* that engage with one another in recurring patterns of interaction, organized around an evolving family of *artifacts*. Through their interactions, the agents

- design, produce, buy and sell, deliver, install, commission, use and maintain artifacts in the family;
- generate new attributions about functionality for these artifacts;
- develop new artifacts to deliver the attributed functionality; and
- construct and maintain new agents and patterns of agent interaction, to ensure that all these processes continue to be carried out, over time, even as the circumstances in which they take place are changing in response to perturbations from inside and outside the market system itself.

A market system can be viewed *functionally* as the collection of the above-listed transformation processes. In the course of carrying out these processes, agents enact others: gathering and interpreting information, setting standards, establishing new entities like trade associations or users groups. All these processes are achieved through interactions among agents – individuals, working groups, divisions, firms, alliances, consortia. Since these interactions taken together deliver the functionality that permit the system to endure over time, they tend to be organized into recurring patterns, with each pattern identifiable by its set of participants, interaction modes, and frequency and duration of interactions.

Each such recurring pattern of interaction between agents defines a link in a network; each such network may be said to carry a system competence; as they are enacted, these competences generate the transformation processes that deliver the system's functionalities. Over time, of course, the transformation processes, the competences that enact them, and the networks that carry these competences change. But in the relatively short term, we may describe the system's organization in agent space as the cross-cutting network of these competence networks.

If we view a market system from a longer time perspective, we notice that it is always undergoing perturbations, which may be generated from processes taking place within the system itself, like the introduction of new artifacts, or may come from outside the system, for example from large-scale macroeconomic shifts. In response, new networks are constructed and others change their structure, either by replacing or adding nodes or by altering the modes, duration or frequency of the linking interaction patterns. Some of these changes may seem to happen spontaneously, but for most of them we can identify *structures* that have provided the opportunity and the means for the changes to happen. Thus, the fluid network organization of a market system is constructed, renewed, and extended by a longer-lasting set of structures that serves to keep the system functioning. We call these structures *scaffolds*, since they shape and support the competence network structure of the system as it undergoes construction and reconstruction. Some scaffolding structures are generated inside the system itself, others come from elsewhere, for example from other market systems, from professions, or from government agencies.

Interaction loci are a particularly important kind of scaffolding structure. They provide a space within which particular types of interactions may take place, as well as rules for managing these interactions.[32] Examples of interaction loci include user groups and trade fairs, trade and professional organizations, standards bodies, and communication media like trade and professional journals, company and organizational newsletters, and websites. Interaction loci are market system level fora in which market conventions may be negotiated, modified and enforced.

The emerging market system for distributed control, organized around LonWorks technology, has already produced a number of important interaction loci, for example:

- LonWorld convention, an annual trade fair. At The LonWorld convention, new products are displayed, new techniques for integrating products into systems are presented and discussed, and successful system solutions are documented. Round table discussions highlight contentious issues in the market system, and the presenters seek to win over others to their way of interpreting the directions in which the system is moving. Often, “air wars” are fought, in which opposing views of the future structure of the system’s artifact space confront each other, before the artifacts that are being touted to dominate that structure have even been designed, much less are ready for production or purchase.
- the LonMark Association, a market system level marketing and standard-setting organization;[33]
- regional and national LonUsers® organizations. In these, the various kinds of agents that intend to “do something” with LonWorks technology – from employees of huge multinational manufacturing or service providers, all the way to engineering consulting firms with a handful of employees – negotiate their respective roles, form alliances, parse the structure of projects in which they must jointly participate, and plan collective actions, of publicity or politics, that will enable LonWorks technology to penetrate further into their local economies and spheres of activity. Most of these groups have been organized “from below,” by agents who have come to understand they stand to gain much more by working with potential competitors committed to the same base technology to expand the domain of that technology, than by battling with them for relative position in a restricted market. Some have been organized from above, by a dominant firm seeking to fill out its offering with contributions from smaller companies that have competences it does not want to supply in-house. In Finland, the national government sponsored an initiative to build up a national competence in building automation and energy management around LonWorks technology, which could spearhead the development of these two industries at the European level.
- a variety of publications and websites, at the international and national levels.

Another important kind of scaffolding structure is cognitive, rather than physical: schema for identifying classes of agents that carry out particular roles inside market systems. Often, these schema are explicitly instantiated by formal certification procedures, or organizations whose members consist of a particular class of agents and which “speak for” the agents in this class, defining their collective identities – what they do, and how they do it. The LonWorks market system features certified LonWorks Independent Developers (LIDs) and Network Integrators (NI’s), the latter of which are

[32] Of course, the space need not physically contain all the participants in the interaction. Instead, it may be mediated by artifacts, as happens with electronic bulletin boards or video-conferencing. As these two examples indicate, however, even such “virtual spaces” can be identified with physical spaces that determine the form of the interactions they support.

[33] See 5.2 below for an extended discussion of The LonMark Association.

organized in an Open System Alliance. In addition, the LonMark Association produces schema for identifying classes of *artifacts* in the market system.

Scaffolding structures are market system level entities. Some, but not all, scaffolding structures have agency – that is, action is carried out "in the name of" the scaffolding structures. The LonMark Association, for example, maintains a website, publishes a journal called Interoperability News, issues press releases about developments in the LonWorks market system, and certifies artifacts that meet its standards for interoperability.

Such market system level agents are established by the agents that comprise the market system, who collectively endow them with certain permissions – but once they attain agency, scaffolding structures can, and usually do, arrogate other permissions for themselves, which may be contested by other agents in the market system, resulting in negotiations for control over various aspects of the structure and functioning of the market system. For example, in 1998 a conflict arose within The LonMark Association over whether or not the Association could decree standards for network operating systems, a move supported by Echelon and the LonMark Association staff. In the end, the opposition – led by two LonMark Association members, a LID and a "big iron" HVAC manufacturer that were jointly developing an operating system for HVAC in competition with Echelon's LNS operating system – successfully blocked the move, restricting the association's standardization domain to software tools and so-called "functional profiles" for devices and components. Thus, establishing scaffolding structures – and particularly endowing them with agency – distributes control in the market system to at least two distinct levels of entities: firm-level agents, like Echelon, LIDs, OEMs, system integrators and so forth,[34] and market-system level scaffolding structures. Of course, control over market system processes is also exercised in part by super-market-system level entities, like national and international legislative, judicial and regulatory agencies. Because of this multi-level distribution of control, it is impossible to understand market system processes solely in terms of actor- or agent-level intentionality. Higher- and inter-level emergent processes must be taken into account as well – an important source of actor-level ontological uncertainty, particularly because such processes are usually poorly narrativized (see section 3).

Thus, to understand how markets come into being and how they are sustained, we need to analyze the market systems in which they are embedded, and in particular the set of scaffolding structures that supports these systems. In this paper, we deal with one aspect of such an analysis, the connection between scaffolding structures and ontological uncertainty, to which we turn next.

5.2 Segregating and controlling ontological uncertainty

Scaffolding structures mediate many aspects of the encounters in which market system agents engage with novel entities – new artifacts, new agents, new kinds of interactions among agents and between agents and artifacts, and new categories in which to frame attributions of identity for agents or artifacts. This mediation happens in different ways. Sometimes, initial encounters with new entities are *off-loaded* from lower-level agents to market system level scaffolding structures; sometimes, the interactions among lower-level agents through which novel entities are assimilated into the market system happen *within* interaction loci provided by scaffolding structures. In either case, scaffolding structures affect the course of interaction streams through which long time- and large space-scale processes fraught with ontological uncertainty happen, thus reducing the ontological uncertainty experienced by lower-level agents – either by removing them from direct experience in these interaction streams, or by moderating the intensity of the streams' currents. We now examine four

[34] Which of course are themselves composed of lower level entities, like actors, working groups and divisions, among whom firm-level control is distributed – despite the apparent claims to the contrary embedded in hierarchical organograms.

different modalities through which scaffolding structures mediate between lower-level agents and novelty: search, information dissemination, interpretation, and channeling.

Search New entities from the outside may have important, even devastating, implications for a market system – like shrink-wrapped pc software had for the hardware word-processor market system. To avoid being blindsided and, more positively, to find new opportunities like markets they might be able to penetrate or technologies and techniques they might adopt, agents need to explore developments outside the market systems in which they currently operate.

Of course, agent space is vast, and exactly where to look, for what, is not so clear, so it is difficult to be systematic about this exploration, particularly for agents that have a lot of other, more pressing things to do – like make and sell artifacts. Moreover, much of what is to be found may be relevant not merely at the individual agent level, but at the market system level. For these reasons, part of the search process may be off-loaded by market system agents to scaffolding structures, often trade and professional associations associated with the market system or even specialized research organizations, like the Electric Power Research Institute (EPRI). Sometimes, these scaffolding structures are even private, for-profit initiatives, market research organizations specialized in a given market system, who carry out research commissioned by particular agents in the market system, prepare reports offered for sale to all market system agents, and sponsor seminars and meetings in which new opportunities for the market system are presented and discussed. For example, Park Associates for years has played a leading role in helping the emerging home automation market system to position itself with respect to existing, larger market systems – and for the agents who operate within the system to figure out their own identities and those of other agents within the system.

Information dissemination New entities do not only come from the outside – they also emerge from interactions inside the market system itself. Identifying them as they happen is critically important for market system agents. While all agents learn privately through their own communication networks, scaffolding structures can operate in a system-level *broadcast* mode to communicate new developments throughout the entire market system. Since the LonWorks market system is under active construction – and has been, for 13 years – it is characterized by a high level of novelty in its configurations of agents and artifacts. Thus, it is not surprising that quite a number of scaffolding structures disseminate information to market system agents about new entities, interaction modes and attributional categories as they emerge, including publications like The LonMark Association's Interoperability News, newsletters put out by national LonUsers groups, informational websites (both open, like The LonMark Association's, and "members only," like most of Open System Alliance's), web news bulletins like the Swedish Smart Home Forum, and web-based LonWorks product directories maintained by The LonMark Association and Echelon.

The most important of the information disseminating scaffolding structures for the LonWorks market system is the now-annual LonWorld trade fair. The first trade fair, called LonUsers, was convened by Echelon in California in November 1991, with around 65 attendees representing over 40 companies. From then, until 2000, two LonUser trade fairs were held each year, one in the US and one in Europe. In 2000, the name was changed to the LonWorld fair, responsibility for its organization was contracted to a German company specialized in putting on trade fairs, and the number of fairs was reduced to one per year.

Since then, well over 1000 people have flocked to the LonWorld convention each year, representing hundreds of companies. Plenary meetings feature addresses by principal market system figures, including Echelon's CEO and COO, representatives of the semiconductor companies that manufacture Neuron chips and companies that pay to "sponsor" the meeting, and special guests from companies that currently figure centrally in some prominent new direction for the market system. These latter have included top managers of companies like Sun, Olivetti, and Cisco that were contemplating strategic alliances with LonWorks technology – as well as people internal to the

LonWorks market system, like the CEO of a new English HVAC company that committed itself completely to distributed control, or a Florida building automation contractor presenting a bold idea for a new kind of "total lifetime" contract for building management systems that he was pioneering.

Most of the presentations at The LonWorld convention are organized into several different "tracks" that concentrate on separate market segments – like industry, buildings, the home, transportation, and energy management. In these presentations, spokespersons from different companies describe new products or projects in various stages of development, emphasizing novel aspects of technique or functionality. There are also tutorials sponsored by companies that have developed new devices or tools they want to sell to other market system agents, as well as very technical sessions for engineers that wish to learn the latest in product development methodology.

The heart of the fair is the demonstration area, where companies display their latest products, and fair participants explore the current configuration of the market system's space of artifacts. Over the years, this part of the fair has become increasingly bigger, and the proportion of the displays that feature products already available for sale rather than "under development" has steadily increased. Some of the booths feature services rather than devices or tools – from internet distributors of LonWorks components to engineering consulting companies. The demonstration area is where participants actually interact with artifacts, playing with new software, inspecting hardware, viewing new kinds of linkages among devices that deliver novel functionality – and, of course, talking with the representatives who man the booths to find out what they do, and what possibilities these activities, and these companies and products, represent for them.

Interpretation In search and information dissemination, the scaffolding structures provide lower-level agents with information that can help resolve some of their ontological uncertainty. In the next two modalities that we discuss, the scaffolding structures play a much more active role, which generate changes at the market system as well as the lower-level agent levels: in interpretation, scaffolding structures help to align agents' attributions about the identity of entities, thus creating system-level shared understandings that undergird market functioning; in channeling, they "control" the formation of new entities that expand the sphere of market system activities, while they confine the disruptive effects of the resulting novelty within the limits of the flexibility that their existing competences impose on market system agents.

To see how scaffolding structures work to align attributions, we examine a particular event from the LonUsers International meeting in Nice in November 1996. In the building automation track at this meeting, there were two particularly hot issues, one about an issue of identity in agent space, the other in artifact space. The first concerned the emergent role of "system integrator": what sort of agent were system integrators for multi-vendor and distributed control systems, and how would the set of activities around such systems be partitioned between the existing major controls companies, the so-called "OEMs," and the system integrators? The second was about the relation between LonWorks technology and a competing communications and control technology, called BacNet, which was in the process of construction by a committee from ASHRAE, the HVAC market system's principal trade association. The ASHRAE committee was dominated by representatives of the big controls companies, and BacNet reflected a much more hierarchically oriented approach to multi-vendor systems than LonWorks networks. LonWorks technology, as we have seen, had been designed to implement sensor- and actuator-level distributed control. In contrast, BacNet had been designed to optimize the connection among relatively autonomous subsystems, each carrying some specific building automation functionality, such as HVAC and security. The subsystems could, through BacNet, be integrated into a facility management system, with a single system view and a limited range of information-sharing capabilities among the subsystems. The artifact issue in 1996 was: are BacNet and LonWorks systems compatible – and if so, what would be their respective roles, for which kinds of building automation systems?

The program for LonUsers groups was under Echelon's control, although for LonUsers groups to function effectively at the market system level Echelon had to be very careful not to be perceived as manipulating LonUsers groups in its own interest. In any event, the two hot issues came together in a panel discussion, moderated by Echelon's AT. The other participants on the panel were two people who worked for big controls companies, one who worked for a big-iron manufacturer, and one who was a partner in a small Swiss engineering and contracting company that had developed a proprietary Lon-based building automation system that they had successfully installed in several new buildings in Switzerland. So the fourth represented one current version of what a system integrator might be, while the other three represented OEMs.

The discussion began with a question from AT: What "buses" (a term then in favor to describe communication and control technologies) are you currently interested in? Immediately three different positions were staked out: the OEM's argued that "special kinds of applications" might require different "solutions," so their companies were trying to support a whole range of "buses," including LonWorks networks and BacNet, when it would be ready. The big iron representative wanted to keep the menu limited, but advanced the claim that BacNet would be better at the facility management level, while LonWorks technology was adapted to the "unit-level, field bus, whatever you want to call it."

In contrast, the Swiss system integrator dismissed BacNet by saying that "it's not available in Switzerland" (in fact, in November 1996 it wasn't available anywhere!), and stating that his company had adopted LonWorks technology in 1992 because it was *real* and it *worked*. He also challenged the view that there really were two distinct "levels" of buses, claiming that using only one communication and control technology offered great advantages in system design, installation, functionality, and maintenance – and his company's LonWorks system would work even for very large projects.

The other three all disagreed, reiterating with increasing rigidity the two-level idea: BacNet and LonWorks networks are "complementary"; "LON is good for the interoperability of simple devices, while BacNet is better at integration—pulling data up to higher-level supervisors". At this point, AT tried to deflect the attempt to relegate LonWorks technology to the secondary role the OEM's were assigning it, by asking whetherEchelon's soon-to-be-released LNS network operating system, might not make LonWorks technology more attractive at the "building management" level. The three OEMs pushed back AT's overture vigorously, getting ever closer to the heart of the matter: "we believe in a central supervisory unit"; BacNet was designed to preserve that unit, LonWorks technology to replace it.

At this point, the discussion shifted from artifact to agent space. Once again, the OEMs began by pushing a pluralism that really defended the current status quo: "Each and every customer has its own needs. System integrators can't be the only channel for building automation, nor the major controls suppliers like Honeywell or Johnson Controls, or companies like Trane that supply component mechanical systems—nor can the owners themselves, serving as their own system integrator, as for example Disney. We'll continue to have a mix of these different integration channels."

Once again the system integrator disagreed with the OEMs. He believed that the role of independent system integrators would become more and more important, since end-users wanted to avoid being locked-in to a single controls supplier, both in purchasing a system and in maintaining it. Introducing end-users into the discussion put the OEMs immediately on the defensive. They responded to the system integrator's argument, claiming that end-users valued the "financial solidity" of the big controls companies; that end-users would buy into multi-vendor systems only when they could have "wire-and-fire",[35] which was several years down the road – and which, when it was finally available, would eliminate the need for the system integrator.

AT then called on a rather agitated man who asked for permission to speak from the floor. The man identified himself as a representative of a "large system integrator;" he wanted to challenge everything that the OEMs had said. His company was already involved in a number of multi-vendor projects, in which they used only LonWorks technology, and what they were delivering was just what end-users wanted. There would *never* be "wire-and-fire," self-designing and –installing systems, and there already were system integrators prepared to give end-users multi-vendor systems at prices lower than the OEMs proprietary control systems, with even more functionality. Then a second system integrator from the audience took the floor. He went even further: he couldn't see why system integrators wouldn't take over "the whole building automation business." At this point, he claimed, what was preserving the "hierarchical" concept of a building automation system composed of collection of component subsystems was not technological constraints on the possibility of total system integration – it was the existing "contract system," which he felt had to change.

Under this onslaught from the floor, which was greeted with choruses of favorable murmurings, the others on the panel backed off. One OEM said: "What is a system integrator? Does he have the responsibility for the entire building automation system? Today he can't, because he can't take responsibility for a large proprietary subsystem. But as systems become more open and interoperable, the system integrator will be willing to take full responsibility—and the customers will welcome that. Contractual issues may change, as innovative system integrators take on the business risk of total system responsibility." Then the big iron man said: "Hierarchical architecture is partially contractual,

[35] That is, systems consisting of standard devices so interoperable that end-users could buy devices, designing and installing the system themselves. Thus, "wire-and-fire" corresponds to "plug-and-play" home entertainment system. The "wire-and-fire" idea ignores the greater complexity of building automation to home entertainment systems.

but it also depends on the fact that different companies have different expertise and knowledge. Given that, it's hard to see that it will go away. But some kind of glue is still needed to make subsystems work together, and that is the role of system integrators. It would be a big mistake to throw away the existing advantages in the structure of the industry." The second OEM then tried to frame a compromise position: "Some companies are just more effective at doing certain kind of things. It takes a big company like ours with the financial capability of making a deal for all the buildings in the US for a company like the Bank of America. There should be mutuality between the different kinds of players in the building controls industry." The other OEM backed him up: "We need to partner. Among manufacturers—and between manufacturers and system integrators. A group of manufacturers, including Honeywell, Phillips, and Landis and Gyr, have put together a brochure on 'openness'. System integrators have to get comfortable with the new products now, in their early days. This doesn't require tight partnerships, but day-to-day working relationships. What percentage of the business in the future will be 'pure OEMs' and what percentage will go to SI's, I can't say at this point."

But the public was not satisfied with these gestures in their direction, and when the discussion got back to the panel, one OEM tried a different tack, identifying a particular role for the OEMs in the currently contested future of the building automation world: "Larger companies have the responsibility to do what they do best. We're good at tools—like the software that our company provides for lighting contractors." The system integrator refused this overture out of hand. "We make all our own tools and we install everything ourselves, with one exception: a large HVAC company that uses OUR tools and components." After some more attempts by the OEMs to define their future roles, the system integrator brought this phase of the discussion to a close: "I think that some of the key products of the big manufacturers will probably survive—room controllers, switchers; but in the future there will probably be only half as many products as there are now, and a lot more solutions to particular problems."

The discussion continued for another half-hour or so, but with a completely different tone. Now everyone on the panel joined in a chorus of praise for a future of lower costs for integrated building automation systems based on LonWorks technology. The only differences emerging in this part of the discussion were about timing – just when all of this would come to pass. The Swiss system integrator thought it was already imminent, while the OEMs on the panel claimed that quite a bit of work remained, particularly in developing specific tools for specific kinds of applications. Nobody mentioned BacNet again, not even in the questions from the floor that concluded the session.

We have described this discussion in some detail, because it illuminates some key features – compressed into a remarkably short time interval – of the processes through which market system level interpretations emerge. The discussion took place before several hundred people, who at this moment represented *all* the relevant agents constructing and contesting the future of building automation around LonWorks technology. At this point in the development of the LonWorks technology penetration into the HVAC market system, opinions had become polarized between those who wanted to preserve the existing structure of this market system as it expanded to incorporate other elements of building automation like security, lighting and so forth, and those who wanted to transform that structure utterly, by collapsing the current hierarchical organization of HVAC control systems, and thus undercutting the agent role structure that supported that organization. The expansion into integrated building automation could not happen without making commitments to specific communication and control technologies, and it was already clear to everyone that end-users would not accept technologies that were closed or proprietary. Competing open technologies were founded upon different ideas about how building automation systems should function and how they would be controlled. Because the discussion took place at LonUsers International, nobody tried to argue that LonWorks technology would have no role in the building automation future. However, it seemed obvious to us that the

OEMs who had been invited to participate in this discussion had agreed on a common line, which they pursued aggressively from the onset: that LonWorks technology would function only as a "low-level" field bus, connecting terminal units to a two- or three- level hierarchy of controllers. For the representatives of the OEMs on the panel, the insidious idea of distributed control that LonWorks technology had been designed to implement would not be permitted to "take over" in building automation.[36]

What happened in the course of the discussion is that this line could not be maintained, in the face of the inability of its defenders to present a credible vision of what was *already* happening in the LonWorks market system and, in particular, in the face of a wave of anger and rejection that swept through the public listening to the discussion. The Swiss system integrator spoke less than any of the other participants in the discussion, but his matter-of-fact arguments forced the others to expose the real basis of their position, and the response of the public required them to backpedal until they had accommodated their line to where the market system as a whole, as represented by the whole set of discussion participants, including those who spoke, murmured or even just gesticulated from the floor, seemed intent on going.

We are not claiming that anyone convinced anyone else of anything during the discussion. Rather, we think that the content of the discussion, within the structure established by LonUsers groups, generated a market system attribution to which everyone in the market system adhered in the events that followed, whether or not they personally believed it was best for them or the right way for the market system to go. Since then, we have rarely heard a serious claim for the primacy of BacNet in any LonWorks market system forum,[37] nor have we again heard OEM's argue for a "division of duties" with system integrators, in which the OEM's would take on all the big jobs, leaving only little projects for system integrators, and that non-centralized system architectures were only feasible if end-users could "wire-and-fire" the system by themselves. OEM's who wanted to preserve their roles and their system architectures more or less intact could no longer expect to achieve these aims working within the LonWorks market system. Future battles over attributions in the LonWorks market system would be fought on other attributional terrain – but in the same kind of forum, through the same sort of process.

Channeling Agents construct new agent-artifact space entities through their interactions, and scaffolding structures channel many of these interactions. This channeling can constrain what kinds of new entities emerge in the market system; it can also induce favored directions for transformations in the structure of agent-artifact space. To the extent that agents understand how channeling works, their ontological uncertainty about the novelty that emerges through channeled processes is reduced – and whether they understand channeling or not, much of their ontological uncertainty concerns entities that will be constructed though channeled processes. Here we explore channeling through some episodes in the history of The LonMark Association.

Almost from the beginning, Echelon understood that a common inter-device communication protocol was not sufficient to guarantee device interoperability. By 1991, the company had developed two strategies to deal with this problem. Institutionally, Echelon intended to establish a certification program, sponsored by the company, which would not only test and certify LonWorks devices

[36] There were other employees of these same OEM companies at the Nice meeting that took a very different point of view of the future of HVAC and building automation. For example, HW worked for Honeywell UK; the US Honeywell Building Automation Division employed a person who had responsibility for "open systems", and this person was much closer to SI's position in the panel discussion. In fact, he was more committed to an interoperable, distributed controls future than SI, who after all worked for a company that produced its own proprietary – even though LonWorks based – building automation system.

[37] Until LonWorld 2003, when it was again up for re-attribution – another instance of ontological uncertainty, in this case ours.

produced by other companies, but would charge for these services and thus generate revenue for Echelon. Technically, Echelon engineers embarked on a definition of Standard Network Variable Types (SNVT's), by means of which the interoperability properties for any device could be specified by a list of the data types, expressed as SNVT's, that it accepted as input and produced as output, along with an interpretation of what these inputs and outputs meant in terms of the device's functions. The working assumptions were that it would be possible to generate a "spanning" set of SNVT's sufficient to encompass the functionality of nearly all devices, and that interoperability could be achieved on the basis of matching and binding SNVT's in and SNVT's out for all the devices in a network.

Both elements of the strategy turned out to be premature. The infant market system of 1991 was not ready to deal with the issue of interoperability. Virtually all of the products incoorporating LonWorks technology produced by other companies in 1991-1994 were "stand-alone" devices or systems, not intended to be linked with others in a LonWorks network. Their manufacturers had adopted LonWorks technology because it speeded up product development time and provided a reliable internal communication and control system for their products. Interoperability posed a chicken-and-egg dilemma. The advantages to developing a LonWorks device whose functionality depended upon its integration into a system with many other devices produced by different manufacturers could accrue only when other manufacturers already had placed many other, complementary devices on the market. In addition, interoperability opened the door to multi-vendor systems and true peer-to-peer, distributed control – which not only threatened the lifetime lock-in to a single controls supplier that was an intrinsic part of the business model of existing controls manufacturers, but required, as we have already seen, new kinds of agent roles, from system integrators to component suppliers, that currently didn't exist. So Echelon's plans to develop its in-house certification system in 1991 kept getting delayed – mentioned as something to work on in the annual "strategy statements" over the next few years, but then not implemented during the year's activities.

By 1994, the situation, particularly with respect to building automation (HVAC and lighting in particular), had begun to change. By then, though, Echelon was finding it increasingly necessary to distribute control among the agents in the LonWorks market system, and the idea that found favor with other market system agents was to set up an independent association, collectively governed, to handle certification and to figure out and implement both the marketing and technical issues associated with interoperability, rather than leave these tasks to Echelon. As a result, the LonMark Association was formally established in May, 1994, with 36 member companies. The LonMark Association has enjoyed a steady growth since 1994. Currently, there are over 300 members, divided into three categories, with different annual fees – sponsors, partners and associates; sponsors are large companies or companies with a big stake in LonWorks technology like Echelon or its semiconductor partners; associates are mainly smaller companies, including LID's and Network Integrators. The LonMark Association is governed by a Board of Directors, consisting of representatives from each sponsor member and elected representatives from the other two membership categories.

It was also clear by 1994 that a purely SNVT-based approach to implementing interoperability would not suffice. The LonMark Association members set to work preparing interoperability guidelines for product developers. Task groups were established, initially organized according to market system – HVAC, lighting, industry, transportation and so forth. Currently, there are 17 task groups – automated food service, building automation systems, elevators, fire and smoke alarms, home and utilities, HVAC, lighting, network tools, refrigeration, routers, security, semiconductors, sunblinds, system integration, transportation and white goods. In each of these areas, task groups define "LonMark functional profiles," which provide standard descriptions of the devices that can incorporated into the kind of system to which the group's work is dedicated. These descriptions list mandatory and optional SNVTs and Standard Configuration Profile Types (SCPTs) for devices of the given type, and explain with which other device types the device is intended to interact, through which input and output SNVTs, to produce which kinds of system-level effects. While LonMarked devices that conform to a given functional profile may also be equipped to provide additional functionality, the set of LonMark functional profiles a task group produces essentially defines a standard system-level functionality, parsing that functionality among a set of standard device types. Thus, ostensibly to facilitate the creation of interoperable systems, LonMark task groups substantially constrain the kinds of devices that will appear on the market and the kinds of LonWorks control networks that market system agents will design and install.

For device manufacturers, the benefits from The LonMark Association's standardization far outstrip the limitations they impose on the ways in which they can gain competitive advantages, particularly in those markets where LonWorks technology has become a de facto standard, like HVAC. The main advantage is clear: functional profiles take a lot of the risk out of the process of developing a product for the market, since the relevant LonMark Association task group has already dealt with the problems of how devices that conform to a functional profile can be integrated into working systems. Manufacturers are certainly free to invent a completely new kind of device that might do wonderful things for a system – but unless they can figure out how to get it to work with devices that conform to LonMark functional profiles, they are unlikely to achieve much market success, unless they produce a whole line of new devices that can deliver all the standard system functionality in addition to whatever new functionality their new devices collectively deliver. And even then, end-users who have already learned to appreciate the benefit of *multi*-vendor systems are likely to be reluctant to adopt a new system, all of whose devices are produced by a single innovative manufacturer.

Clearly, then, there is a lot at stake for manufacturers in the work of LonMark task groups, inducing them to make sure that task groups come up with functional profiles that are compatible with the system architectures they prefer. At the beginning, because of the expense involved in dedicating engineer-hours to market system level design work, the task groups were dominated by representatives from the biggest manufacturing companies, who tried to design profiles with an uncanny resemblance to their own company's existing products and architectural preferences. For example, the first proposed functional profile for a Variable Air Volume terminal HVAC unit did not have a temperature SNVT input to it. This meant that the VAV unit could not possibly control itself, and the logic for that control would have to be located somewhere else – presumably, in one of the centralized control computers that the big control companies who then dominated the HVAC task group produced! As a result of incidents like this, almost all companies in the LonWorks market system made sure that they or allies they trusted participated in all the task groups working in areas for which they might want to produce devices or design and install systems, and the functional profiles that these task groups generated reflected compromises among the different kinds of agents with interests in the application areas toward which the task groups were directed. The technical problem of designing functional profiles for device types and making them cohere into "standard" systems became the arena in which market system level, shared attributions of artifact identity for automatically controlled systems of various kinds were worked out.

An interesting issue that the LonWorks market system has to handle collectively is just what constitutes the "base technology" around which the entire market system is organized. Clearly, the LonTalk protocol and the Neuron chip are part of the base technology, and application-specific tools and devices are not – but there is quite a lot of gray area between these two extremes. Sometimes, even the *extremes* are called into question. For example, from the early 1990's, the Electronic Industry Association, the economically and politically powerful trade association for home electronics, sponsored an alternative standard for networked control for home automation, called CEBus. For several years, Echelon and advocates of CEBus, especially a small Florida company called Intellon, which marketed a CEBus compatible chip set, carried out a furious "air war" for putative control of a home networking "market" that hardly existed; the market that did exist was dominated by neither

LonWorks technology or CEBus, but by an older, not particularly reliable master-slave communication technology called X-10. In 1996, the EIA nearly succeeded in pushing through legislation in the US Congress that would have mandated that all set-top boxes be CEBus-enabled. This legislation would have practically guaranteed CEBus domination in the peer-to-peer home networking "revolution," when it would finally happen. LonWorks market system agents and their allies were able to mobilize a political counter-attack, assisted in Congress by Silicon Valley's representative, which succeeded in forestalling EIA's project. But the experience convinced Echelon and other LonWorks market system agents that some way had to found to neutralize EIA's support for CEBus.

One ingredient in this strategy was to participate in EIA's standards committee and propose that the official standard be a "smorgasbord", with LonWorks technology as in approved alternative to CEBus. After a lot of hard work, the strategy paid off, and LonWorks technology was incorporated in EIA's standard, much to the dismay of the CEBus allies. This successful effort had an unexpected consequence. Some of the CEBus allies had complained that LonWorks technology wasn't really "open". Since Echelon licensed the base technology at a very low rate and didn't produce Neuron chips itself, it was difficult to pin the label of "proprietary" on Echelon, though serious efforts to do so were undertaken. However, the CEBus advocates were able to score points when they protested the "monopoly" position of the Neuron chip: why couldn't the LonTalk protocol be implemented on other chips, with alternative memory, input-output and application programming capabilities? Echelon reluctantly[38] agreed to formally open the LonTalk protocol and to sponsor an alternative implementation, which was carried out by a LID. Thus, the Neuron chip itself was partially replaced as an element of the LonWorks "base technology" by a public software version, which could be implemented as firmware in other chips.

In 1998, Echelon increasingly saw their new LNS network operating system as the crown jewel of their product line. They decided to push to make it a LonWorks market system standard – that is, to incorporate it into the market system's base technology. So they tried to have the LNS operating system approved as a standard by The LonMark Association. However, in 1998 they were no longer in the position they occupied in the early '90's, when they were essentially the sole arbiter of what constituted the market system's agent-artifact space structure. Recruiting other agents into the market system required that they also distribute control over that system. As mentioned earlier, Echelon was unsuccessful in getting the LNS product approved as a standard, since other LonMark Association members were developing a competitive product. As a compromise, network operating systems were declared by the LonMark Association to be "off-limits" to defining standards; since then, a whole set of technology types have been declared "off-limits" for the association. However, the LNS operating system appears to have become the *de facto* standard operating system in the LonWorks market system, even though the competing product is still available for whoever wants to use it. In the end, Echelon turned out to be right – but this time, the "market", not scaffolding structure channelling, would decide.

5.3 Scaffolding structures and generative relationships

Scaffolding structures can – and often do – promote the formation of generative relationships among market system agents. In this section, we discuss how they provide frameworks in which relationships with high generative potential may form and the generative potential of existing relationships may be enhanced.

Interaction loci endow market system agents with permissions to engage in particular kinds of structured discursive interactions. The rules they provide for these interactions tend to channel

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[38] Reluctantly, because a multiplication of chip types would complicate interoperability and make assigning unique identification numbers to the processors at each network node more difficult.

discourse into ongoing market system activities, from panel discussions and question-and-answer sessions after presentations at the LonWorld fair, to more goal-oriented activities like the construction of functional profiles in The LonMark Association. Hence the permissions that underwrite a scaffolding structure's discursive settings may contribute to align the directedness of the discourse participants and increase the generative potential of relationships which they may form.

The participants in these structured discursive interactions are frequently very heterogeneous, since they may span the entire spectrum of market system agents, from representatives of large, dominant control companies, through founders of new start-up companies oriented around LonWorks technology; from network integrators to design engineers; from semiconductor salesmen to energy management contractors. While, as we have seen, heterogeneity – particularly attributional heterogeneity – is a key constituent of generative potential, *too* much heterogeneity may also lead to mutual incomprehension, and even cultural or social animosity. Scaffolding structures' permissions restrict the range of topics participants can discuss and the illocutionary modes they may employ. As in diplomatic interactions, when the level of participant heterogeneity is the highest, these permissions tend to enforce the strongest limits about what can be said, on which subjects, with which tones – thus helping to keep participant directedness aligned and mutual directedness above the level at which discussions break off. Thus, the structure of interaction loci discourse can increase the probability that discourse participants may discover partners with whom they may share a high generative potential, and, through channelling, they may actually increase the generative potential of the relationship that begins to form.

Scaffolding structures may often provide action opportunities around which potentially generative relationships can consolidate. For example, LonTech is a non-profit organization to whose members are Swiss LonWorks market system agents interested in building automation. In 1996, LonTech had 24 members, ranging in size from Johnson Controls to small engineering firms. According to its founder, building projects are complex, both in human and technological relationships. The local market structure was not ready to support the kind of integration that distributed, interoperable systems require. Building owners have separate relations with electrical, mechanical and controls contractors, the architect, and so on. As a result, they lack an integrated view of their projects. In addition, they operate under severe time pressures, do not understand networks, nor do they trust little companies. While the contractor partners try to maintain a project-level focus on their individual competences, they are afraid of losing their piece of the business, and they may lack confidence in each other. As the project gets under way, the building owner begins to have his horizons opened as he understands about the possibilities offered by LonWorks technology, but then he does not understand its limitations. Throughout the project, many coordination problems arise: in particular, how can work be organised in parallel? At the end, the customer is left with a too complex user interface, and the partners haven't documented the system, just its parts. Thus, the problems are mostly on the *human* side of the network—problems of trust, coordination, and communication.

LonTech was set up as a possible solution to these problems. Its mission is to "build community" among the potential partners in a LonWorks building project, to develop a form for partnerships, to educate one another in order to make communication possible about the different facets of a project, and to inform customers about LonWorks technology and its applications. To accomplish this mission, LonTech sponsors a number of activities, all of which provide opportunities for its members to work together on particular project. Perhaps most important, it set up a permanent exhibition at its headquarters in Thun, in which various members display functional components connected in a multi-vendor system. Constructing and updating this exhibition represent action opportunities for Swiss LonWorks market system agents to learn how to work together – and to make their artifacts function together in a system that can help convince potential clients to specify distributed, interoperable control for their building projects. In addition, LonTech offers training courses open to third parties, including system integrators, architects and building owners. LonTech members work with people from Echelon and local technical universities to develop these courses. LonTech also maintains a data-base of components, and project management and quality control support material. It also provides a forum in which LonWorks system integrators exchange practical lessons learned during the course of their projects. Finally, LonTech developed a set of rules and procedures to make job cooperation easier, including a definition of global system structure, a project process checklist, quality control and interface definitions, and responsibility checklists. All these activities have provided opportunities for the Swiss LonWorks market system agents to work together to create necessary cognitive, procedural and artifactual infrastructure for their local market system – and in the process of doing these things, to develop generative relationships with one another.

6. Coda: phenomenology, theory and innovation

At one level, the main point of this paper is to present the phenomenology of innovation processes associated with ontological uncertainty, from the level of the individual actor to that of the emerging market system.[39] According to our conception of innovation, ontological uncertainty is endemic in innovation processes, because innovative agents participate in constructing large-scale transformations of agent-artifact space, and the transformations that result from their interactions do not, indeed cannot, correspond to intentions at the level of individual actors. We have seen, through the examples from our research on Echelon and the LonWorks market system, how narratives, generative relationships and scaffolding structures all work to enable agents to cope with ontological uncertainty, in part by temporarily holding it at bay, in part by off-loading, segregating and channelling it into specific venues where it is "controlled" through highly structured interaction modalities, and in part by uncovering, exploring and even exploiting it in the context of special kinds of agent relationships. We argue that the phenomenology associated with ontological uncertainty is so central to innovation processes that no attempt to understand innovation that fails to deal with it can hope to succeed.

At another level, the paper claims to have introduced three theories – the narrative theory of action, the theory of generative potential, and the theory of scaffolding structures – that purport to explain aspects of the phenomenology associated with three different spatial-temporal levels of innovation processes. The three together by no means form a "complete" theory of innovation, a project on which we are currently working. So what are these theories, what work do they do towards providing insight into innovation processes, how might they be evaluated, and how might they be developed? We conclude this paper by providing a sketch of our answer to these questions.

For us, the aim of any process theory is twofold: to provide a minimal language with which one can construct causally convincing[40] narratives of historical instances of the target processes, and which may, through specialization and further abstraction, lead to mathematical models that can be used to explore the theory's implications for such instances and to generate predictions about observable outcomes of instances. Thus, theorizing is a continuing dialogue between theory and narrative and theory and model, refining and deepening the theory through confrontation with the test-beds of historical data and mathematical implication. A *rich* theory is one that has the capacity to sustain this dialogue over time. Of course, this depends not just on the "artifact space" aspects of the theory – but also on the agents that can be recruited into developing the dialogue, through historical case studies like our LonWorks project and through the construction of mathematical models linked to the theory.

We suggest three criteria to evaluate theories such as those we have proposed in this paper. First, a process theory should be *well-founded*: that is, its central concepts should be causal, not

[39] We thank Chuck Sabel for pointing out to us the purely phenomenological interpretation of the first five sections of the paper.
[40] Convincing, that is, to the narrative communities to which the theorist belongs, or with which he identifies.

epiphenomenal. The central concepts of a theory express the ontological commitments of the theorist: which entities matter for the processes the theory addresses, through which modalities these entities interact, and what are the interaction dynamics – that is, the changes they bring about in the entities' structures and properties and their interaction modalities, and the order in which the interactions occur. Exploring the implications of these ontological commitments typically requires mathematical or computational models; convincing historical narratives are the means whereby their well-foundedness can be demonstrated. In this paper, the stories we tell from our LonWorks study are designed to show that narrative structure and narrative logic, generative potential and generative relationships and scaffolding structures are causal, within, of course, the scope of the theories presented. For example, the scope of the narrative theory of action is much more restricted than the scope of Savage decision theory: it is designed to explain how individual actors generate action as they confront ontological uncertainty, not to explain the consequences of their actions, which we regard as simply unpredictable in general at the individual actor level.

Second, a process theory should be *rich*: that is, it should generate explanations and predictions of a wide range of observable innovation phenomena. It is often relatively easy to determine that a theory cannot be rich, because it is clearly crafted around one particular kind of phenomenon in a strongly ad-hoc manner. By contrast, as we claimed above, it takes considerable time and effort to determine just how rich a theory may be – and in the process of doing so, we should expect many transmutations of the theory, as models and case studies lead the theorists to modify and extend the theory's central claims. We think all three of the theories we presented in this paper may turn out to be rich, but it is premature even to speculate about why we believe that to be the case. Here, the proof of the pudding is definitely in the eating, and we hope at least that others may be convinced to join us in the feast.

The third criterion is that a process theory should be *productive*, in the sense that it suggests new kinds of empirical research that should be carried out to give insight into the structures through which the target process is carried out and the functions that it fulfills. Our theories identify many such research projects, from the identification of narrative communities relevant to innovation processes and the sets of narrative structures associated with each community, to the development and application of techniques to measure quantitatively the generative potential of relationships through which new attributions and artifacts have been or may be developed, to the classification of different kinds of scaffolding structures and their roles in the construction and consolidation of new market systems, as well as a formal description of the constrained communication processes through which their market system functionality is achieved.

Thus, at the theoretical level, this paper is more programmatic than definitive. Interpreting the phenomenology the paper highlights, by means of a series of process theories that are well-founded, rich and productive, which are linked together into a general theory of innovation, will be a project for many people working over a long time.

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