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Abstract

This paper explores how interorganizational net-works coevolve with technology in the modern flight simulation industry. Since industries characterized by complex technologies, like flight simulation, rely on cooperative groups such as technical committees, task forces and standards bodies to adjudicate the process of technological evolution, we focus on these groups and term them 'cooperative technical organizations' (CTOs). Focusing on CTOs enables a multi-level examination of interorganizational networks, as individuals represent their employing organizations in CTOs, mapping into overlapping membership patterns which generate community-wide networks. We develop a set of propositions on the emergence, growth and re-formation of CTO networks, and explore how the evolution of these networks both shapes and is constrained & by technological outcomes in the flight simulation industry. We argue that varying levels of technological uncertainty between eras of ferment (high uncertainty) and eras of incremental change (low uncertainty) engender fundamentally different modes of network evolution: social construction during eras of ferment, and technological determinism during eras of incremental change. More specifically, during the era of ferment, movement of new members into the CTO community enables the re-formation of interorganizational networks which select among competing technological alternatives. The selection of a dominant design, however, constrains the evolution of network structure, as subsequent CTO membership remains relatively consistent. These dynamics have strategic implications for firms, as the era of ferment presents a window of opportunity where firms must seek to manage these community-level networks and selection processes to their advantage.

Disciplines

Business Administration, Management, and Operations

THE COEVOLUTION OF COMMUNITY NETWORKS AND TECHNOLOGY: LESSONS FROM THE FLIGHT SIMULATION INDUSTRY

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THE COEVOLUTION OF COMMUNITY NETWORKS AND TECHNOLOGY: LESSONS FROM THE FLIGHT SIMULATION INDUSTRY

ABSTRACT

We explore how interorganizational networks coevolve with technology in the modern flight simulation industry. Since industries characterized by complex technologies, like flight simulation, rely on cooperative groups such as technical committees, task forces, and standards bodies to adjudicate the process of technological evolution, we focus on these groups and term them "cooperative technical organizations" (CTOs). Focusing on CTOs enables a multi-level examination of interorganizational networks, as individuals represent their employing organizations in CTOs, mapping into overlapping membership patterns which generate community-wide networks.

We develop a set of propositions on the emergence, growth and re-formation of CTO networks, and explore how the evolution of these networks both shapes and is constrained by technological outcomes in the flight simulation industry. We argue that varying levels of technological uncertainty between eras of ferment (high uncertainty) and eras of incremental change (low uncertainty) engender fundamentally different modes of network evolution: social construction during eras of ferment, and technological determinism during eras of incremental change. More specifically, during the era of ferment, movement of new members into the CTO community enables the re-formation of interorganizational networks which select among competing technological alternatives. The selection of a dominant design, however, constrains the evolution of network structure, as subsequent CTO membership remains relatively consistent. These dynamics have strategic implications for firms, as the era of ferment presents a window of opportunity where firms must seek to manage these community-level networks and selection processes to their advantage.

Research on the relationship between technology and organizational communities has differed on whether and when communities shape technology or technological evolution determines community-level organization (e.g., Bijker, 1995; Smith and Marx, 1994). In support of a social constructivist approach to technological evolution, Noble (1984) asserts that the dominance of numerically-controlled machine tooling technology over record-playback technology resulted from cooperative activity between the Massachusetts Institute of Technology, the General Electric Corporation, and the U.S. Air Force. Similarly, Ahlstrom and Garud (forthcoming) argue that the use of high-cost renal treatments such as dialysis and kidney transplants have become the dominant approach in the U.S., rather than the low-cost, alleviative modality of dietary protein restriction, due to the reenforcing activities between medical institutions, government, and insurance companies. In contrast, others suggest that technological outcomes constrain subsequent organizational evolution. Aitken (1985) demonstrates that closure on vacuum tube-based components as the dominant design for radio systems in the early 20th century set the stage for the formation of RCA to elaborate and sustain the competencies and patent positions of General Electric, Westinghouse, AT&T, and others. Hughes (1983) uses the concept of “technological momentum” to illustrate how the AC or DC electrical supply systems dominating in the U.S., Germany and Britain subsequently shaped the development of related institutional activities like curriculum development at universities.

Recent treatments of the coevolution of organizations, technologies, and institutions suggest that both perspectives may apply. Interorganizational networks and communities socially construct technological change; in turn, technological outcomes determine the evolution of organizations and communities (Nelson, 1990; 1994; Powell, 1990; Rosenkopf and Tushman, 1994, Van de Ven and Garud, 1989; 1994, Bijker, 1995). In this paper, we explore the impact of technological uncertainty on modes of technological and organizational evolution. We examine this coevolution of technology and community organization by focusing on the interorganizational network formed by members of voluntary cooperative groups such as task forces, technical committees, and standards groups. Examining these types of groups, which we term "cooperative technical organizations" (CTOs), enables exploration of how community-level organization both influences and responds to technological change, as CTOs link various constituencies in pursuit of technological standards and subsequent technological trajectories.

Since theory is underdeveloped in this area, our purpose is to generate propositions about both the emergence and evolution of CTO fields and how technological evolution is intertwined with these issues. We ask whether stages of the technology cycle -- eras of ferment and eras of incremental change -- are associated with the evolution of community network structure. We position technological uncertainty as the driving force that varies across these stages and motivates CTO activity by individuals, organizations and institutions. Specific patterns of CTO emergence and growth are aggregated into CTO networks, which enables exploration of how network structural characteristics like cliques and centrality contribute to the social construction of technology. Taken together, these issues suggest that sequences of organizational, interorganizational, and institutional activities create a context within which competing technologies are selected, and industries emerge or reform (Aldrich and Fiol, 1994).

We explore and extend our propositions through a case study of the modern flight simulation industry, using a combination of qualitative and quantitative methods to illustrate CTO dynamics in the industry between 1958 and 1992. Flight simulators are extremely complex, low-volume products, and their use is strongly regulated for commercial air traffic. This industry is fertile terrain in which to explore the linkages between technological evolution and networks, as the degree of interorganizational cooperation in the interest of technological progress is high (Miller et al., 1995). Since the flight simulation arena illustrates heightened CTO network dynamics, we also address the generalizability of our results and offer some theoretical guidance for industries with products that are less complex and/or less regulated.

Flight Simulation: The Context

Since the Wright Brothers' historic flight, engineers and managers alike have been interested in on-the-ground devices that can train pilots in the skills necessary for flight. Yet most training took place in the air, posing economic and safety considerations. By the mid-1970s, however, two alternative flight simulation approaches had emerged in commercial and military arenas. These alternatives vied for resources as well as social and political support, and are summarized in Table 1.

> *Full flight simulators* (FFSs) cost $15 to $20 million dollars, and they faithfully replicate the flight experience by integrating cockpit instrumentation with full motion and visual capability. Use of FFSs was supported by several constituencies: commercial airlines, whose training arms were typically run by ex-commercial pilots; regulatory bodies, typically staffed by ex-military pilots; and aircraft manufacturers. While pilots supported FFSs because of their belief that "realism" was the primary dimension for measuring training effectiveness, aircraft manufacturers supported FFSs because they generated a larger market for the sale of their cockpit instruments, aeronautical models, and flight test data. CTOs supporting FFS-based approaches formed by 1977 included the Air Transport Association's Training Committee, the Federal Aviation Administration's Advanced Simulation Plan Working Group, and the International Air Transport Association's Flight Simulation Technical Committee. In 1989, the Royal Aeronautical Society's International Simulator Standards Working Group was formed to standardize this approach internationally.
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> In contrast, *flight training devices* (FTDs) cost $1 to $3 million dollars, having no motion or visual capabilities. This type of device can train a pilot in certain skills, and a series of different FTDs can, in theory, accomplish much of the training requirement. Use of FTDs was supported by academic and military researchers, who believed that transfer of training could be accomplished more effectively with a specific focus on human factors and learning processes rather than faithful replication, by regional and general airlines who could not afford the price of FFSs, and by flight schools, who trained regional and general airline pilots. CTOs supporting FTD-based approaches, such as the American Institute for Aeronautics and Astronautics' Flight Simulation Technical Committee, the Federal Aviation Administration's Advanced Flight Training Device Qualification and Advanced Qualification Plan Working Groups, and the University Aviation Association’s Simulation Committee, did not emerge until the mid-1980s and beyond.

Without a clear technological perspective on whether FFSs or FTDs were more appropriate means of pilot training and certification, and despite the availability of both approaches, use of FFSs for commercial aircraft training and certification became the regulated norm in 1980. We attribute this outcome to the ability of FFS-supporting constituencies to organize, inform and persuade regulatory bodies in the late 1970s coupled with the lack of such activity by the FTD-supporting constituencies during this time frame. Only after the subsequent organization of FTD-supporting constituencies in the mid-1980s has the flight simulation community at large begun to take up the question of replacing some FFS-based training with FTD-based training. We demonstrate the role of CTO networks in the evolution of flight simulation technology systematically throughout this paper.

THEORY

Cooperative Technical Organizations, Technological Communities, and Levels of Analysis

We define a "cooperative technical organization" (CTO) as a group that participates in technological information exchange, decision-making, or standards-setting for a community. Common names of CTOs include "working groups", "standards bodies", "technical committees", "task forces", and "interest groups". Membership of a CTO spans multiple constituencies, such as firms, government, and academia. Yet membership in a CTO is not open to all: The leaders of CTOs limit group sizes and select new members, who are invited to attend[1]. This controlled membership is critical to CTO's influence: While the American Institute of Aeronautics and Astronautics' Flight Simulation Interest Group numbered well over a thousand members, only 17 members of the flight simulation community constituted AIAA's Flight Simulation Technical Committee at its founding. It was in the small technical committee that key representatives from research and military organizations discussed, deliberated and defined technical options, not in the large interest group.

CTOs contain collections of experts that decide upon and institutionalize technological perspectives (e.g., Aldrich and Sasaki, 1995; Farrell and Saloner, 1988; Van de Ven and Garud, 1994). The sources of expertise vary in the flight simulation community, including engineering training and experience, regulatory position, and piloting experience. These industry-wide groups are critical components in a process of population-level learning (Miner and Haunschild, 1995), serving as mechanisms that create, select, and retain technological routines such as the FFS-based and FTD-based paradigms for pilot training and certification. CTOs facilitate innovation and learning by serving as venues for information exchange and know-how trading (Rogers, 1995; von Hippel, 1987), and by issuing standards or position papers that are disseminated throughout the flight simulation community.

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[1] For government-sponsored CTOs, however, attempts to limit CTO membership may be illegal.

At the same time, CTO activity promotes isomorphism in response to regulatory pressures, technological uncertainty and ambiguity, and professionalization (DiMaggio and Powell, 1983).

The CTO field offers a powerful window into a broader set of community-level dynamics. By "community", we mean the set of organizations that have a stake in the development of the product class. Within communities, we can observe a variety of actors, differences in the ability of each actor to influence technological change, and a host of inter-organizational linkages between these actors. As portrayed in Figure 1, CTOs link key individuals who represent firms, government, academia, and other institutions. At the same time, these influential individuals and organizations participate in multiple CTOs, and these common members link CTOs.

These cross-cutting organizational constructs make it difficult to specify only one level of analysis (DiMaggio, 1994). Our ultimate focus in this paper is on community structure generated by CTO membership, and how this structure evolves with technology. To understand the processes of structural evolution, however, we turn to specific mechanisms at several levels of analysis. Using the CTO as the unit of analysis, we can examine formation and dissolution of CTOs, as well as examining the purpose and sponsorship of these groups. Such processes may be considered the "macrodynamics" of community evolution. Likewise, processes that focus on the individual CTO member as the unit of analysis may be considered the "microdynamics" of community evolution. Individual patterns of participation in CTOs may vary with time and reflect individuals' personal and professional motivations, or they may reflect the strategic intention of their employing organizations. Each level is examined to understand the mechanisms that underlie observed variations in community structure.

Emergence and Growth of CTOs

Literature on the emergence of new industries and the activities which enable this emergence suggests that the set of CTOs will grow with an industry. Van de Ven and Garud (1994) demonstrate that the emergence of a new technology-based industry, cochlear implants, relied upon an accumulation of institutional activity by CTOs that adjudicated uncertainty through rule-making and ensured conformance via rule-following. This perspective is elaborated by Aldrich and Fiol (1994), who acknowledge the struggles by entrepreneurs to achieve legitimacy for a new industry via activity at organizational, intra-industry, inter-industry, and institutional levels. Oliver (1990) argues the formation of interorganizational relationships such as trade associations is motivated by multiple contingencies. Beyond creating legitimacy, CTOs promote stability through uncertainty reduction and manage asymmetry by enabling consensus-building among diverse constituencies like regulators and manufacturers.

CTOs can be considered minimalist organizations because they require minimal resources for founding and sustenance (Halliday, Powell and Granfors, 1987). Initial labor and capital costs of minimalist organizations are low; the formation of CTOs requires only the recognition of a technical issue and the selection of members from the larger technological community to meet and address this issue. Furthermore, CTOs rely on the infrastructures of their members' organizations to support work time, travel expenses, and to host meetings. As such, patterns of evolution for minimalist organizations are characterized by relatively simple foundings and few dissolutions (Aldrich et al., 1990). Furthermore, since CTOs are populated by individuals who represent their employing organizations, as the set of CTOs grows, so too does the set of opportunities for individuals and organizations to participate in this activity. This set of opportunities expands further as the membership base of each CTO is likely to grow over time[2]. Taken together, these institutional and ecological perspectives on CTO macrodynamics and microdynamics suggest that the populations of CTOs and of the individuals (or organizations) participating in CTO activity will be continually growing as institutional infrastructure grows along with the industry.

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[2] Consider the evolution in membership of a typical CTO. A small coalition of actors recognizes an area for cooperative technological innovation and forms a CTO to address it. Initially, membership of this CTO is relatively homogeneous, especially when it is sponsored by trade associations (groups of manufacturers or users) or standards institutions (groups of manufacturers). For example, in flight simulation, the University Aviation Association formed a simulation committee with members representing flight schools. They later invited flight training device manufacturers to join them. Likewise, the American Institute of Aeronautics and Astronautics formed a flight simulation technical committee with members from research labs and the military. In subsequent years, manufacturers and regulators were invited to join. Again, this intra-CTO growth increase the set of participation opportunities available to the community.

Technology Cycles as Context for CTO Emergence and Growth

These perspectives on the evolution of CTO fields, however, fail to acknowledge that the evolution of these technology-focused groups is interdependent with the very technologies they were formed to control. One way to explore this interdependence more deeply is through an understanding of technology cycles. The two key features of the technology cycle model are technological discontinuities and dominant designs, which demark eras of ferment and eras of incremental change (Tushman and Anderson, 1986; Sanderson and Uzumeri, 1995, Utterback and Abernathy, 1975). Technological discontinuities usher in eras of ferment, where technical substitution, design competition, and change in the existing technical order occur; technological uncertainty is high (Clark, 1985). The rise of a dominant design decreases technological uncertainty, causing engineers to direct their attention to refining existing products and processes during the subsequent era of incremental change (Utterback and Abernathy, 1975; Basalla, 1988; Dosi, 1984). Subsequent technological discontinuities restart this technology cycle. Technological discontinuities and dominant designs have been used as indicators that parse differential patterns of firm entry, innovation, success, and exit (cf. Anderson and Tushman, 1990; Suarez and Utterback, 1995; Baum, Korn and Kotha, 1995).

Technological discontinuities interrupt predictable, puzzle-solving patterns of technological evolution and initiate an era of ferment. During eras of ferment, dimensions of merit and their measurement become unclear; this increased technological uncertainty characterizes competition between and among technological regimes. For example, in the medical diagnostic imaging industry, doctors found it difficult to judge between competing technologies (X-ray, nuclear, ultrasound, and CT scanner) because they were unsure whether to base their decisions on properties of resolution or scan time (Yoxen, 1987). Likewise, the competition between single- and multichannel cochlear implant devices took several years to resolve because of the difficulty of measuring a device's ability to discriminate speech (Van de Ven and Garud, 1994). Producers, doctors and users could not determine whether to rely on the FDA-approved single-channel device or to heed reports from users that multichannel devices seemed to be more effective. Increased uncertainty is met by renewed efforts toward coalition-building (Pfeffer, 1981) as sponsors attempt to garner support for their technological variants (Wade, 1995). Discontinuous technological change spurs the emergence and proliferation of new organizational forms, interorganizational relationships, and affiliations that span industry boundaries (Meyer, Brooks and Goes, 1990). These dynamics contribute to the social construction of technology during eras of ferment (Tushman and Rosenkopf, 1992).

While coalition-building may re-form inter-organizational linkages and drive technology during the era of ferment, the emergence of a dominant design constrains technology, organizations, and networks during the era of incremental change (Tushman and Rosenkopf, 1992; Utterback and Abernathy, 1975). Like Abernathy's (1978) rich description of how dominant designs mark organization-level transitions between fluid and specific states, we argue that the dominant design has equally profound community-level effects. Critical problems are defined, legitimate procedures are established, technical puzzles are solved, and community norms and values emerge from interaction among interdependent actors (Van de Ven and Garud, 1989). Practitioner communities develop industry-wide procedures, traditions, and problem-solving modes that permit focused, incremental technical puzzle-solving (Constant, 1987). During the era of incremental change, technological determinism operates, as existing relationships are solidified and elaborated within the confines of the dominant design. Ultimately, the community's beliefs about technological limits of the dominant design may lead to searches for new alternatives (Henderson, 1995), particularly as returns to investment narrow, sowing the seeds for the next technological discontinuity.

The assumption that the social construction of technology is more prevalent during the era of ferment while technological determinism is more prevalent during the era of incremental change, as developed above, underlies our next four propositions. Using the technology cycle and these contrasting modes of social construction and technological determinism as frames, we develop a more fine-grained approach to CTO evolution and growth. During the era of ferment, technical activity centers around uncertainty reduction through the definition of technical attributes and the selection of technical alternatives. CTOs provide a forum to manage divergent views and interests, serving as loci for consensus-building and adjudication by bringing representatives from various organizations and coalitions together to define technological outcomes. During the era of incremental change, in contrast, technical activity is limited to information exchange and problem-solving within the dominant technological paradigm. Such activity can take place within the established CTOs that have supported the emergence of the dominant design. Subsequent technological discontinuities will, however, renew the wave of CTO foundings.

> *P1: While CTOs will always proliferate, the rate of CTO foundings will increase during eras of ferment and decrease during eras of incremental change.*

Since CTO members are individuals who represent their employing organizations, both the competitive motivation of the employing organization and the professional motivation of the individual should be considered. The power to influence technological change and reduce uncertainty will accrue to individuals and organizations that participate in CTOs, because this participation enables control of technical agendas and decision-making at the community level (Pfeffer, 1981). This power yields competitive advantage for firms as well as professional value for individuals. When technological uncertainty is high, then, both the organizational and individual motivation to participate in CTOs will be greatest. Potential CTO community members will seek out such activity more intensely during the era of ferment than during the era of incremental change.

> *P2: The rate at which individuals (and organizations) enter the proliferating CTO community will increase during eras of ferment and decrease during eras of incremental change.*

Aggregating Macrodynamics and Microdynamics Generates Community Structure

The dynamics of CTO formation (macrodynamics) and the entry of individuals into CTOs (microdynamics) underlie the broader changes in network structure that shape (or are constrained by) dominant designs. To understand community structure, consider that certain key members of the technological community belong to multiple CTOs. In flight simulation, for example, an operations manager of one airline belongs to national and international trade association committees as well as working groups sponsored by national and international regulators. Similarly, a U.S. regulator participates in international regulatory efforts but is also invited to participate in professional society and trade association technical committees.

Any pair (or larger subset) of CTOs may be compared to evaluate how many members they have in common[3]. These common members form "weak ties" between CTOs (Granovetter, 1973), as each CTO has access to the same knowledge and contacts belonging to each of the common members. Examining the common membership among the full set of CTOs shows the *structure* of relationships in the community. CTOs with common members form *cliques*, which may represent common approaches to technological development across multiple CTOs[4]. In other words, although the industry-wide technical endeavors may be scattered among a multitude of CTOs, cliques may pursue common, agreed-upon approaches to technological development due to their common members. Furthermore, the patterns of common membership ties among CTOs establish varying levels of *centrality* across the set of CTOs. Since common membership ties enable communication of alternatives and selection criteria across CTOs, those CTOs which span communication paths between other CTOs have more potential to control communication in the network (Freeman, 1978). Centrality is frequently associated with power (e.g., Burt, 1991; Burkhardt and Brass, 1990), so the technological approaches of central CTOs are more likely to dominate other alternatives.

Ecological perspectives on structure highlight the reenforcing nature of these networks. McPherson (1990), in his study of membership in voluntary civic associations, demonstrates that commonality in membership across these organizations continually grows as current members of each group recommend new members for admission. Likewise, several of our informants made comments

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[3] This commonality in membership may be derived from the individual members themselves or from their organizational affiliations.

[4] Clique-like approaches to innovation have also been used by Clark and DeBresson (1990), who speak of "innovation poles" as well as Teubal et al. (1991), who speak of "networks of innovators".

suggesting that selection of CTO members is based on social ties. One informant claimed that ". . . selection has more to do with 'who you know' and 'when you knew them'. . ." and another stated that ". . . individual names can become well known even in a relatively short time. This in itself probably helps significantly to promote those individuals to membership of CTOs." In this sense, one might expect CTO community structure to continually consolidate through common membership ties, as well-known individuals and organizations are increasingly represented in each CTO. Indeed, several informants described the set of CTOs as "incestuous". We argue, however, that the technology cycle influences this consolidation dramatically. Specifically, technological discontinuities will disrupt these patterns of network consolidation; while the evolution of community structure is ordered during eras of incremental change, it is chaotic during eras of ferment, when previous relationships and sources of power are devalued by uncertainty and new opportunity (Rosenkopf and Tushman, 1994). Furthermore, these transitions in network structure are driven by the macrodynamics and microdynamics of CTO formation and growth. Higher technological uncertainty during the era of ferment drives higher rates of CTO formation and growth, destabilizing and re-forming established network structure, as new interorganizational networks coalesce to shape critical dimensions of merit (Astley and Fombrun, 1983; MacKenzie, 1987). During the era of incremental change, however, reduced technological uncertainty yields lower rates of CTO formation and growth, consolidating and elaborating network structure. In Bijker's (1995:282) terms, "closure" on an "exemplary artifact" is associated with a "hardened network of practices, theories, and social institutions." This leads to two general propositions about the evolution of community structure over the technology cycle:

> *P3: CTO cliques are disrupted by technological discontinuities but stabilized by dominant designs.*
>
> *P4: The distribution of power among CTOs is disrupted by technological discontinuities but stabilized by dominant designs.*

Technology and Community: Some Contingencies

Taken together, our propositions suggest that varying levels of technological uncertainty over the technology cycle influence rates of CTO emergence and individual entries, which jointly influence community network evolution (see Figure 2). During the era of ferment, high technological uncertainty yields more CTO formations and more new entrants to the CTO community. These additional groups and members give rise to coalition-building to adjudicate technological uncertainty, resulting in re-formation of CTO cliques and centrality. These changes in network structure are harbingers of the eventual dominant design, as technology is the "product of social negotiation" (Hounshell, 1995). Convergence on a dominant design then solidifies these networks; during the era of incremental change, reduced technological uncertainty yields fewer CTO formations and fewer new entrants to the CTO community. Less flux in groups and membership is, in turn, associated with the stabilization of CTO cliques and centrality; community organization evolution is constrained by the very dominant design it re-formed to select. Thus, the selection of a dominant design demarks the transition between two fundamentally different modes of evolution: social construction of technology during the era of ferment, and technological determinism during the era of incremental change (Tushman and Rosenkopf, 1992; Hughes, 1994, Bijker, 1995). The next technological discontinuity restarts this cycle.

Our theory suggests vigorous CTO fields serving as the locus of innovation for technological communities, which we explore in the flight simulation industry. How might technological complexity alter or moderate these dynamics? Tushman and Rosenkopf (1992) suggest that the influence of sociopolitical processes on the selection of a dominant design is accentuated for products like flight simulators. Here, multiple, diverse dimensions of merit characterize the performance of competing technologies, and heterogeneous, diverse communities of organizations, professionals, and institutions jointly determine this selection. For *systemic* technologies, where multiple, interdependent components are linked via sophisticated interfaces to create the end product, these processes of community-based technological selection are most prevalent (Barnett, 1990; Miller et al., 1995) and we observe network modes of organization and governance (Powell, 1990; Garud and Kumaraswamy, 1995). In contrast, for nonassembled or simple assembled products, technological competition can be resolved by superiority on easily measured dimensions of merit by single or focused communities; the locus of innovation remains within firms, and the influence of sociopolitical dynamics on the process is minimal (Tushman and Rosenkopf, 1992; Powell, 1990).

> *P5: The coevolutionary effects described in Propositions 1-4 increase with product complexity; systemic technologies and products will be associated with more CTO activity than non-systemic technologies and products.*

Industries characterized by strong regulatory environments will also experience heightened CTO activity. “Legal and regulatory requirements ... provide the impetus for interorganizational relationships that otherwise might not have occurred voluntarily” (Oliver, 1990). Similar to the effect of technological complexity, regulatory pressures move the locus of innovation beyond the firm to the community level: regulation introduces diverse dimensions of merit -- safety, public benefit -- to technological competition, and regulatory actors enlarge the technological community, increasing the role of sociopolitical dynamics among the community members for convergence on a dominant design. The role of these “epistemic communities” has been well documented in the political science literature (e.g., Adler and Haas, 1992).

> *P6: The coevolutionary effects described in Propositions 1-4 are accentuated when regulatory presence is strong.*

METHODS

Data were collected from key players in the flight simulation industry. This set of key players was generated in a snowball fashion. Initial respondents were located by contacting all of the members of two CTOs -- the Air Transport Association's Training Committee and the American Institute of Aeronautics and Astronautics' Flight Simulation Technical Committee. These CTOs were chosen because together, their memberships spanned suppliers, manufacturers, users, regulators, military bodies, and academics. Respondents from these groups were, in turn, asked to cite other key people in the flight simulation community. Two subsequent stages of sample selection followed from these citations. To reduce attrition bias, we supplemented this sample with other names available from archival membership rosters. When these rosters were not available, we asked respondents who had participated to enumerate others who were also participating.

Each respondent completed a questionnaire on his/her employment history, CTO memberships, and the technological evolution of flight simulators; he/she also participated in a follow-up phone interview to ensure consistency of responses. Fifty-six of one hundred sixty-six questionnaire recipients responded (34%). Since many of the recipients participated in multiple CTOs, the sample included 139 CTO memberships.

Eras of Technological Change

Flight Simulators as Systems of Interdependent Components. To identify stages of the technology cycle, an understanding of the composition of a flight simulator is necessary. Flight simulators can be classified as closed assembled systems (Tushman and Rosenkopf, 1992). They are composed of computing hardware, motion systems, visual systems, and flight instruments integrated via software and mathematical models, as shown in Figure 3. While the evolution of each component can be discussed separately, these paths are interdependent, as progress in one component can enable or retard progress in other components.

> *Software and Mathematical Models.* The software and mathematical models are the engines of flight simulation. Since every other subsystem depends on the software for coordination and direction, the software is considered the "core" subsystem of the flight simulator. Manufacturers of full flight simulators (also called integrators) develop proprietary models and software, which are somewhat customized for each product. All commercial simulators do, however, perform each test mandated by regulatory requirements. The software is supplemented by the data pack, a "black box" of proprietary equations and flight test data that integrators must buy from aircraft manufacturers.
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> *Computer Hardware.* The use of analog computers in the 1940s and 1950s gave way to electronic digital computers in the 1960s. Within the digital computing regime, competence-enhancing developments increased the speed of computing for simulation, which added to the complexity of the software and modeling, and thus realism of the simulation process. The evolution of parallel processing capabilities in the 1980s may be used to power multiple simulators concurrently.
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> *Flight Instruments (Avionics).* Electro-mechanical instruments gave way to electronic flight management systems in the mid 1970s. Traditionally, simulators contained the

> actual flight instruments of the plane, and these instruments were "stimulated" by the simulation software to display readings to the pilot. Today, however, debate has arisen about the worthiness of this approach, and many players advocate the simulation of these instruments.
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> *Motion Systems* with three degrees of freedom were the hallmark of modern flight simulators, beginning in 1958. The development of hydrostatic bearings enabled the rise of motion systems with six degrees of freedom during the 1970s. Today there are questions about the value of motion for training purposes, as researchers are unsure whether the additional knowledge offered with motion capability is transferred to real flight situations. Recent military applications have experimented with simpler motion systems (that is, fewer degrees of freedom) as well. Closed Circuit TV *visual systems* (where cameras were driven over model boards) gave way to Computer Generated Imagery (CGI) in the 1970s.

Identifying Dominant Designs and Technological Discontinuities. We chose to ask respondents about “controversies” rather than “dominant designs” or “technological discontinuities” so that we would address system-level issues as well as subsystem-level issues. Controversies represent battles between alternative system-level approaches that are only resolved over extended periods. As such, controversies indicate eras of ferment, which are resolved by the emergence of dominant designs.

The vast majority of references to system-level controversies represented two major arenas. Based on these references, one dominant design and one technological discontinuity for flight simulation systems are identified on Figure 3. The 1980 “Total Training and Checking” standards in the U.S. (later termed the more descriptive “Zero Flight Time (ZFT)” standards, as a pilot could accomplish all training requirements on a full flight simulator without ever flying the aircraft) represent the dominant design. The interdependent transitions in subsystem technologies in the 1970's culminated in the issuance of ZFT standards by the Federal Aviation Administration in 1980. All full flight simulators used in the United States built after this time conformed to ZFT standards, which required the use of the more advanced subsystem technologies. Note that the ZFT standards may be considered a regulatory event that cemented the technological design. The ZFT standards were instituted by regulators, but only after a host of technological changes as the subsystem level enabled the development of simulators sophisticated enough to perform all training and checking maneuvers. Furthermore, the ZFT standards set out a trajectory of incremental innovations in full flight simulators that would become required in installments over the 1980s.

As flight simulators evolved as required by this standard, users recognized that returns to investment in the technology were diminishing and began balking at the overuse of technology in the standard. For example, full daylight visual capabilities cost approximately one million dollars more to provide than dusk capabilities, and it became increasingly clear after the development of dusk capabilities that daylight capabilities might be unnecessary. During this same period, researchers were discussing the value of six degree of freedom motion systems, and manufacturers were experimenting with parallel computing. In response, in 1987, the Chief Administrator of the FAA signaled to the flight simulation community its willingness to consider "modular simulation systems[5]" in addition to full flight simulators. Modular simulation is the use of a set of flight training devices in conjunction with full flight simulators, rather than the sole use of full flight simulators. This change in regulatory stance heightened technological uncertainty; new challenges to the community from 1987 until 1992 have included the question of which partial devices are appropriate as well as how to combine these appropriate partial devices into an overall simulation/training system. This era of ferment, focused on the development of modular simulation systems, hinges on the availability of distributed computing as well as improved understanding of training transfer and other human factors issues. No subsequent dominant design has arisen, evidenced by the fact that no commercial airline had submitted a full proposal for modular simulation to the FAA under their "Advanced Qualification Plan" by 1993.

To confirm our interpretations of these technological transitions, copies of an early and a subsequent draft chapter on the evolution of flight simulation technology were circulated amongst the survey respondents. Each of the respondents were contacted for clarifications and corrections, which were reflected in subsequent iterations of the text. All respondents were ultimately comfortable with our classification of these three different eras of technological change: an era of ferment lasting until 1980,

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[5] This terminology has the unfortunate result of confounding Henderson and Clark's (1990) distinction between "architectural" and "modular" innovations. Modular simulation, as defined here, is an example of Henderson and Clark’s “architectural innovation”, as it changes the relationships between components in a flight training system.

an era of incremental change from 1981 until 1986, and a subsequent era of ferment from 1987 until 1992. Furthermore, this interpretation is also consistent with the research of Miller et al. (1995) in the flight simulation industry.

Community Organization Variables

CTO foundings. The year in which a CTO was founded was obtained from the leader of the CTO and validated in written documentation. If the year was not available in this fashion, the earliest year in which a survey respondent indicated participation was used. Note that this method could cause one to estimate the founding date to be later than it actually was. The number of CTO foundings was then totaled for each year. Table 2 displays the founding, dissolution and sponsorship of the CTOs studied. Figure 4 graphs the number of foundings and the overall number of CTOs in existence during each year of the study[6].

Individual entries. The year in which an individual first entered the CTO community was obtained by taking the earliest year of CTO membership from the respondent's list of CTO membership years. The number of individuals entering the CTO community was then totaled for each year. Figure 5 graphs the number of individuals entering the community in a given year. Data on individual membership was also transformed to capture how employing organizations maintained membership in CTOs. Longitudinal patterns of entry based on organizational affiliation are strongly correlated with the

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[6] One might question whether all CTOs could be obtained in such a fashion. While there is no guarantee that all existing CTOs were included, two factors suggest that the list is reasonably comprehensive. First, in the three stages of sampling, the number of new CTOs included in the data set decreased from 15 to 11 to 4, respectively. Second, a review of all articles listed under the Business Periodicals Index heading of "Flight Simulation" from the trade publications Flight Training, Aerospace, Flight International, Simulation Newsletter, Civil Aviation Training, Aviation Week, Interavia, and Air Transport World did not indicate activities of any other groups than had been identified through the questionnaire and interview process.

individual patterns and are not reported here.

Community structure. Network ties between CTOs are operationalized as the number of members each pair of CTOs has in common. While membership data are available on a yearly basis, these data were aggregated across each era of the technology cycle to facilitate comparison between eras. Common membership matrices were created which specify the maximum number of members CTOs i and j have in common during any year of the era. The matrices were analyzed using STRUCTURE (Burt, 1991). "Strong components analysis" was used to generate **cliques** of CTOs based on these common membership ties, meaning that each CTO in a clique must have at least one member in common with *every* other CTO in the clique[7]. We also used UCINET (Borgatti et al., 1992) on the common membership matrices to estimate the betweenness **centrality** of each CTO in each era.

Note that the common membership ties are generated by counting the number of common individuals, rather than common organizations. We chose to use individuals, rather than organizations, as linking mechanisms between CTOs because many of our individuals representing the same organization were in very different parts of the organization (functionally and geographically), and did not

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[7] Strong components analysis is but one decision rule for creating cliques. Another candidate would be "weak components analysis", where an organization in a clique must have at least one common member with *any* other organization in the clique. Obviously, weak components analysis generates larger cliques because the criteria for belonging to a clique are less restrictive. Strong components were chosen over weak for this analysis for two reasons. First, the size of the community is small enough that most CTOs merge into one or two cliques of weak components, reducing the granularity of the analysis. Second, if cliques are viewed conceptually as innovation poles, then it is sensible to insure that a set of common individuals (and therefore, organizations such as firms, governmental or academic bodies) are represented throughout the clique, bringing common agendas to all CTOs in the clique. We do, however, denote common membership ties between strong components cliques (and isolates) in our results.

share information with each other. Therefore, it would be unrealistic to assume they represented common interests in the community-wide activities.

"Key" CTOs. We designated CTOs as "key" when they satisfied two criteria. First, our respondents ranked the five CTOs that "contributed the most to the development of flight simulation" out of the full set of CTOs. We aggregated these responses to yield overall rankings of CTO contribution. Six CTOs fell into the top third of both contribution ranking and centrality values and were designated as key.

RESULTS AND DISCUSSION

In this section, we use the flight simulation data to illustrate the structure of CTO networks and the associated dynamics of CTO formation and individual entry during each era of our study period. Then, we revisit and refine our coevolutionary model. To simplify this discussion for the reader, we summarize characteristics of the networks during each era of our study period in Table 3, and interpret these evolutionary trends below. Readers who wish further exposition of the individual CTOs and the network structure will find more detailed descriptions and diagrams of network structures in our appendix.

Overall Trends in CTO Network Evolution Over the Technology Cycle

First era of ferment. The first era of ferment provides a baseline to understand the longer-term evolution of CTO networks. During this time, a total of 7 CTOs operated, populated by 18 members in our sample. (For network detail, see Figure A-1.) Of these 7 CTOs, 2 were key CTOs: The Advanced Simulation Plan Working Group sponsored by the Federal Aviation Administration, and the Flight Simulation Technical Committee sponsored by the International Air Transport Association. Both of these key CTOs focused their efforts on development of full flight simulation approaches. At the same time, representatives of commercial airlines (users of simulators) constituted the majority of the sample, populated the key CTOs, and participated in additional CTOs. Thus, users supporting full flight simulation approaches generated a dominant clique which included both key CTOs.

Since the airlines recognized the economic benefits of training in simulators rather than aircraft, they used the CTO venue to convince regulators that such training would be sufficient. Thus, the impetus for full flight simulation standards started with simulator users rather than regulators or even simulator manufacturers. Indeed, one of the regulators charged with developing Zero Flight Time standards suggested that during the first era of ferment, "...all the technical expertise was outside the government." Organized users were able to satisfy regulatory concerns. In contrast, support for the flight training device approach was scattered among isolated CTOs in the network, such as the Flight Simulation Technical Committee sponsored by the American Institute for Aeronautics and Astronautics. Given this community structure, how could the socially constructed outcome have been anything but the Zero Flight Time, full flight simulation-based standard?

Era of incremental change. After the adoption of the Zero Flight Time standard in 1980, the subsequent era of incremental change was characterized by an elaboration of the baseline network. (For network detail, see Figure A-2.) During this time, a total of 8 new CTOs were formed, more than doubling the total number of CTOs in the community to 15. Yet the number of participants in the CTOs only rose from 18 to 22 (seven new entrants, three exits). Key CTOs from the previous era of ferment remained key and were joined by one other CTO that also pursued full flight simulation issues, the Training Committee sponsored by the Air Transport Association. Once again, simulator users predominantly defined the community and hence the common membership ties; the dominant clique retained its power in the community.

Apparently, the determination of Zero Flight Time standards created a technological paradigm that constrained change in both technology and community networks during the era of incremental change. Few new individuals or organizations entered the community; rather, incumbent individuals and organizations formed additional CTOs. Some of these new CTOs tackled questions such as how to model wind shear and how to avoid simulator sickness -- problems arising within the confines of the

Zero Flight Time, full flight simulation paradigm. Other new CTOs were user groups established to aid in the transmission of common information arising from the paradigm. Thus the tenor of efforts during the era of incremental change was shaped by an overarching understanding of what a full flight simulator should look like, what tests it should perform, and which organizations controlled these types of questions. In essence, much of the community evolution occurring during the era of incremental change was the formation of new groups by existing community members, and this CTO proliferation created an organizational division of labor among tasks performed by many of the same individuals.

Second era of ferment. With the rise of modular simulation approaches in 1987, the network dynamics of the second era of ferment contrast starkly with those of the previous era. (For network detail, see Figures A-3 and A-4). During the second era of ferment, the number of CTOs in the community again grew, from 15 to 24 (twelve new CTOs, three disbanded). Yet the most dramatic increase was in the number of individuals participating in CTOs, which nearly doubled from 22 to 43. This near-doubling was accomplished through 22 new participants and only 1 dropout. This wave of new participants included a sizable contingent of regulators, who achieved much more expertise in their ranks through hiring individuals from numerous simulation-related areas. This increased expertise stemmed from regulators' efforts to manage the innovation process more proactively; both regulators and non-regulators in our sample concurred that this transition had occurred.

Three new CTOs join the set of key CTOs from the previous eras, including the Advanced Flight Training Qualification Group sponsored by the Federal Aviation Administration, the International Simulation Standards Working Group sponsored by the Royal Aeronautical Society, and the Simulator Technical Issues Group sponsored by the Air Transport Association. The positioning of these six key CTOs in the network structure reflects the competing technologies under consideration during this era: One dominant clique, which we call the "Old Guard", is bound by common user ties, and includes two key CTOs supporting full flight simulator-based approaches. The other dominant clique, which we call the "New Guard", is bound by common regulator ties, and includes two key CTOs supporting flight training device-based approaches. The remaining two key CTOs occupy boundary-spanning positions between the two Guards, as they share common members in both camps.

Since modular simulation approaches increased technological uncertainty, firms and other organizations attempted to shape technological developments and heighten their awareness of competing frameworks by entering new individuals into the CTO community. The community itself created a host of new CTOs to address questions outside of the traditional full flight simulation paradigm, such as the standardization of flight training devices and the construction of modular flight simulation systems. These questions are much broader than those addressed during the eras of incremental change, for they challenge existing understandings of what a simulation system should be composed of, and how users can construct such systems. The combination of a doubling in CTO community membership and the formation of groups that challenged the existing paradigm dramatically altered community structure, as old cliques fragmented and CTOs recombined into new cliques.

As regulatory representatives gained technological legitimacy, other CTOs were more likely to include them among their members. Regulatory personnel created bridges between the academic and practical arenas: The presence of regulatory personnel in the traditionally academic groups sparked their recognition of modular simulation opportunities, which they have opened up for commercial discussion under their Advanced Qualification Plan.

During this era of ferment, the re-formation of networks again enabled the social construction of flight training device-based approaches to pilot training and certification, which now compete with the full flight simulation-based approaches. The two dominant cliques in this network reflect the tension between the two approaches. Yet the two key CTOs that span the Old Guard / New Guard divide suggests some continuity of perspective and membership among these two factions. In particular, reconciliation of these battling systems and the linked organizational communities that support them may be achieved by hybrid approaches for pilot training that download much of the traditionally FFS-based training to FTDs. This blend of the two approaches is further illustrated with the fact that most of the traditional full flight simulator manufacturers have added higher-end flight training device product lines.

Revisiting Theory

Our findings yield mixed support for our propositions. In support of Proposition 3, community networks were observed to evolve differently after dominant designs than after technological discontinuities, and we attribute these differences to varying levels of technological uncertainty. During the era of incremental change, the preexisting entities elaborate a division of labor through the creation of new CTOs with similar membership ties. In contrast, during the subsequent era of ferment, the preexisting network of CTOs is fragmented and recombined by the entry of new members and the changes in incumbent members' CTO affiliations. This reorganization of preexisting coalitions occurs as the community struggles to redefine the concept of a flight simulation system as a modular training system. Manufacturers of flight training devices are entering the community, regulators are taking a more active role in the innovation trajectory, and suppliers of subsystems have begun to participate. Many of the new CTOs have limited ties to the community, being linked to one of the two Guards but not to other new CTOs. At this stage, the multiplicity of CTOs forces individuals and organizations to place innovation bets, as there are limited resources and time for participating in these many forums, and therefore common membership among these many peripheral CTOs is low. Nonetheless, it is clear that a "battle of the Guards" complements the technological battle between FFS- and FTD-based simulation approaches in the latest era of ferment.

Yet the mechanisms driving this network evolution follow different rhythms. Although Proposition 1 suggested that CTO founding rates would be higher during eras of ferment, we found that CTOs are continually founded, irrespective of the technology cycle (See Figure 4). Yet while CTOs proliferate during all eras of the technology cycle, none of the six key CTOs were founded during the era of incremental change. Evidently, CTOs founded during eras of ferment, while no more numerous, have more lasting potential to resolve uncertainty and to advance technological development. Due to the high technological uncertainty during this era, the purpose of these CTOs is more likely to focus on system-level issues like the technical composition and functional standards of flight simulators and their associated certification processes. Similarly, Proposition 4 suggested that the power distribution among

CTOs would be disrupted by technological discontinuities, but we found that CTOs which had obtained key status never lost this status. Evidently, key CTOs focused on system-level issues necessarily bridge multiple constituencies to achieve their goals, which makes them less susceptible to shifts in power even when other network characteristics adjust.

In contrast, individual entries do seem to vary with the technology cycle, supporting Proposition 2 (See Figure 5). Waves of entries during the eras of ferment and a relative paucity of entries during the era of incremental change suggest the value of entering cooperative activity during the era of ferment; technical contributions can resolve uncertainty and benefit both professional reputations and organizational positions. At the same time, CTOs are soliciting members more heavily during eras of ferment to build the coalitions needed to support their variants during these windows of opportunity.

CONCLUSIONS

A focus on the CTO field enables systematic exploration of how interorganizational communities of practice coevolve with technology. The multiple levels of analysis inherent in the CTO population, its membership, and its network structure offer a set of lenses that simultaneously capture both community and organizational processes interdependent with technological evolution, as summarized in Figure 2. We believe that firms must understand these dynamics and seek to exploit them strategically to gain competitive advantage.

Networks affect technology and technology affects networks. If this coevolution is contingent on technology cycles, then technological discontinuities generate windows of strategic opportunity for firms to participate in shaping emerging standards during the era of ferment. After closure on a dominant design reduces technological uncertainty and constrains subsequent network evolution, firms must still consider how network dynamics may trigger or hinder the next technological discontinuity.

We illustrated the social construction of technology by analyzing CTO cliques and CTO centrality, structural properties of interorganizational networks. Social construction was associated with the era of ferment, where more dramatic change in CTO memberships formed new cliques and newly formed CTOs joined the set of key CTOs. The waves of entries into the CTO community during eras of ferment suggest that individuals see value in CTO participation during this time, as the era of ferment presents a window of opportunity to shape technology and accumulate valuable professional expertise. We are not convinced, however, that organizations perceive this same value, as anecdotal evidence suggested that there is very little oversight of the patterns of CTO activity maintained by the firm overall.

Literature on the management of innovation has typically focused on managing networks and activities *within* firms. Yet our theory and our case demonstrate the importance of managing *across* firms and other organizations in the community. This activity, as we suggested in Propositions 5 and 6, should be particularly critical for systemic, regulated products like flight simulators. The role of CTO networks in shaping technological outcomes has significant implications for strategic management. We argue that firms need to manage their overall patterns of CTO activity to deploy their people strategically, constructing network links that coalesce multiple CTOs and constituencies in support of their technological approaches. While we believe that these links are currently generated by key individuals with multiple memberships, coordination and placement of multiple individuals coupled with information-sharing among these individuals could accomplish the same ends. Similarly, the relationship between community networks and technology has implications for national industrial policy as well. Understanding how firm and individual participation in CTOs shapes technological outcomes offers windows of opportunity during eras of ferment when policy makers can entertain formation of new groups to reconstruct bases of technological support and power.

The flight simulation industry is but one venue to examine cooperative voluntary relationships; we cannot eliminate the criticism that our results are idiosyncratic to this industry. We chose to focus on a single case so that rich qualitative data could be used to illuminate our quantitative data. In this way, anecdotal evidence highlights the dynamics of evolutionary processes. Nonetheless, generalizability of this study may be limited, and future studies should examine to what extent the role of CTO networks and their evolution may decrease in venues with less complex products, reduced regulatory presence, or more diffuse market structures.

Most importantly, CTO participation is but one mechanism from which we can induce an overlay network of interorganizational relationships. Our understanding of knowledge flows across communities will be enhanced as we study multiple types of network ties simultaneously. Complementary research must examine both contractual and informal means of knowledge transfer, including alliances and mobility of professionals, and track how these mechanisms are interdependent with CTO participation. This multiplicity of ties, taken together, constitutes a “knowledge network” in which firms are embedded. Future research must focus on how a firm’s position in this network can influence its performance, and suggest how firms can alter their positions strategically. This work is underway.

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TABLE 1

TWO APPROACHES FOR PILOT TRAINING AND CERTIFICATION

	Full Flight Simulator (FFS)	Flight Training Device (FTD)
Cost	$15-20 million	$1-3 million
Advantage	Realism	Lower-cost transfer of training
Proponents	Commercial airlines Ex-pilots (regulators) Aircraft manufacturers	Academic & military researchers Regional & general airlines Flight schools
Supporting Cooperative Technical Organizations (year founded)	ATA Training Committee (1961) IATA Flight Simulation Technical Committee (1972) FAA Advanced Simulation Plan (1977) RAeS Int'l Simulator Standards Working Group (1989)	AIAA Flight Simulation Technical Committee (1984) FAA Advanced Flight Training Device Qualification (1987) FAA Advanced Qualification Plan (1989) UAA Simulation Committee (1990)

TABLE 2

FORMATION, DISSOLUTION AND SPONSORSHIP OF CTOS

Years	CTO	Type of Sponsor
1961	Air Transport Association Training Committee (ATATRAIN)**	Trade Association
1968	Atlas Consortium (ATLAS)	Consortium
1972	International Air Transport Association Flight Simulation Technical Committee (IATAFSTC)**	Trade Association
1974-1983	American Institute of Aeronautics and Astronautics Working Group on Simulation Facilities (AIAAWGSF)	Professional Society
1976	International Air Transport Association Data Pack Exchange Working Group (IATADPX)	Trade Association
1977	Federal Aviation Administration Advanced Simulation Plan Working Group (FAAASP)**	Tr. Ass'n and Regulator
1979	Harris User Exchange (HARUE)	Supplier
1982	Rediffusion Simulator Users' Group (REDSU)	Manufacturer
1984	American Institute of Aeronautics and Astronautics Flight Simulation Technical Committee (AIAAFSTC)	Professional Society
1984	International Air Transport Association ARINC Subcommittee (IATAARIN)	Trade Association
1985	ARINC Systems Architecture Integration (ARINCSAI)	Standards Body
1985-1988	Simulator Sickness Working Group (SSWG)	Professional Society
1985	Federal Aviation Administration Helicopter Standards Working Groups (FAAHS)	Regulator
1985-1988	Wind Shear Working Group (WSWG)	Trade Association
1986	Gould Working Group (GOULDWG)	Supplier
1987-1992	Federal Aviation Administration Advanced Flight Training Device Qualification Group (FAAAFTQ)**	Regulator
1988	Society of Aerospace Engineers Simulation Committee (SAESC)	Professional Society
1988	Royal Aeronautical Society Flight Simulation Groups (RASFSG)	Professional Society
1989	Federal Aviation Administration Advanced Qualification Plan (FAAAQP)	Regulator
1989	Royal Aeronautical Society International Simulation Standards Working Group (RASISS)**	Professional Society
1990	Air Transport Association Simulator Technical Issues Group (ATASTIG)**	Trade Association
1990	University Aviation Association Simulation Committee (UAASC)	Trade Association
1991	Joint Aviation Authority Simulator Standards Working Group (JAASS)	Regulator
1991	Aviation Rulemaking Advisory Committee (ARAC)	Governmental Body
1992	Federal Aviation Administration Rotary Wing Working Group (FAARW)	Regulator
1992	Royal Aeronautical Society Flight Simulation Technical Committee (RASFSTC)	Professional Society
1992	Modeling and Simulation Industry Steering Group (MSISG)	Governmental Body

** Key CTO

TABLE 3

CHARACTERISTICS OF COMMUNITY NETWORKS
BY ERA OF THE TECHNOLOGY CYCLE

	First Era of Ferment	**Era of Incremental Change**	**Second Era of Ferment**
Number of CTOs	7	15	24
- Entries	na	8	12
- Exits	na	0	3
Number of participants	18	22	43
- Entries	na	7	22
- Exits	na	3	1
Key CTOs	FAAASP IATAFSTC	FAAASP IATAFSTC ATATRAIN	FAAASP IATAFSTC ATATRAIN FAAAFTQ RASISS ATASTIG
Source of common membership ties	Users	Users	Users and Regulators
Clique structure and composition	One dominant clique that includes all key CTOs	One dominant clique that includes all key CTOs	Two dominant cliques split four key CTOs and are linked by two other “boundary-spanning” key CTOs
Change in overall network structure	na	Elaboration of cliques from first era of ferment	Fragmentation and recombination of cliques from prior era of incremental change

FIGURE 1

COOPERATIVE TECHNICAL ORGANIZATIONS (CTOs):

An Overlay Network

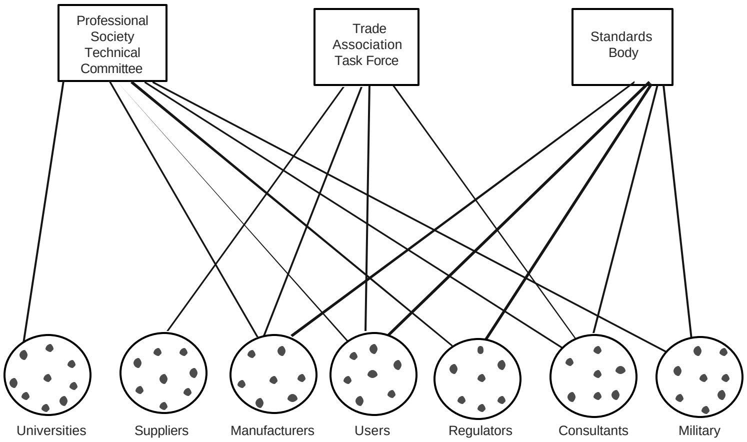


FIGURE 2

THE COEVOLUTION OF NETWORKS AND TECHNOLOGY

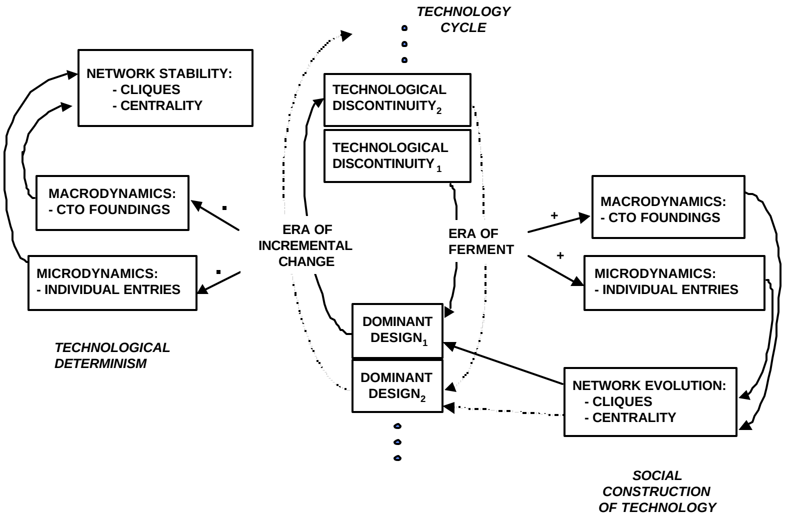


FIGURE 3

TECHNOLOGICAL EVOLUTION OF FLIGHT SIMULATION

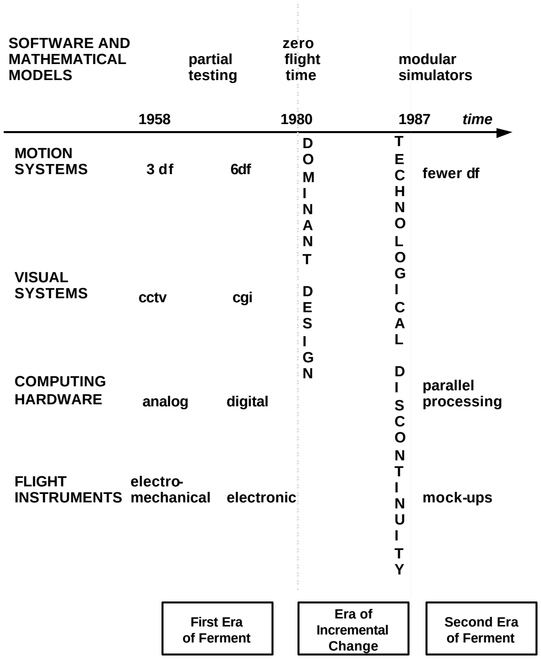


Figure 4

CTO FOUNDINGS AND DENSITY

1958-1992

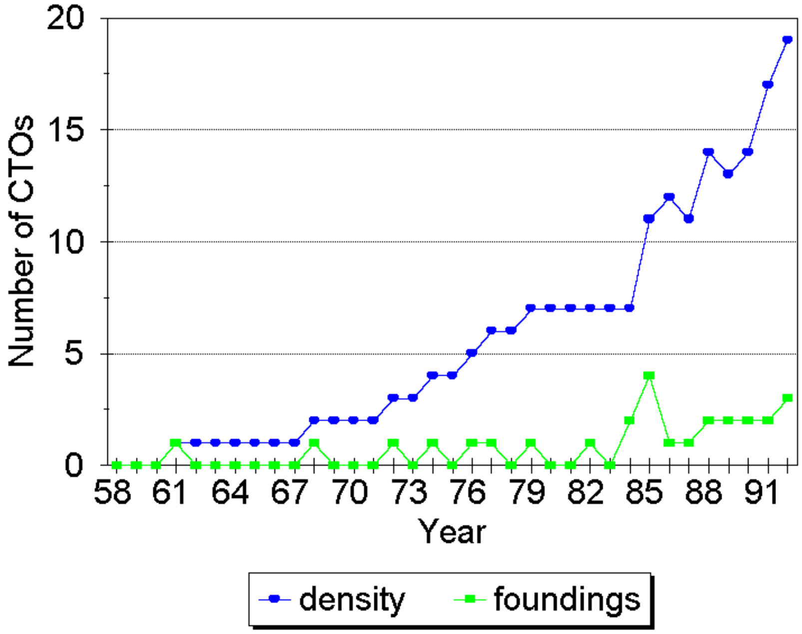
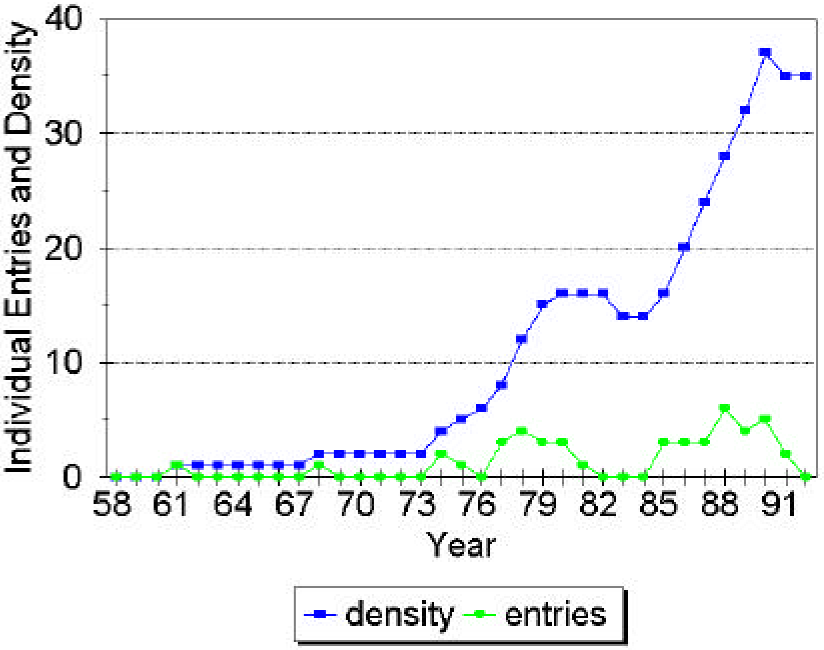


FIGURE 5

CTO COMMUNITY ENTRIES AND DENSITY

INDIVIDUAL REPRESENTATIVES



APPENDIX

DETAILED DESCRIPTIONS OF NETWORK STRUCTURE AND CTOS

First Era of Ferment

Figure A-1 displays the seven CTOs active during the first era of ferment, which were populated by 18 individuals from our sample. One clique is evident: three CTOs (the Federal Aviation Administration's Advanced Simulation Plan Working Group (FAAASP), the International Air Transport Association's Flight Simulation Technical Subcommittee (IATAFSTC) and Data Pack Exchange Group (IATADPX)) share common members from the airlines.

The dashed lines in Figure A-1 represent the situation where CTOs have some common members, but not extensive enough ties to be incorporated into the strong components clique. In this way, the ATLAS consortium and the Air Transport Association's Training Committee (ATATRAIN), include some airline representatives among their members. These two weakly-linked CTOs, like the main clique, focused primarily on user benefits, but their activities did not center around pushing regulators to adopt standards. The ATLAS consortium was formed to share equipment and knowhow among European air carriers (when simulators were much less prevalent than now), and the Air Transport Association's Training Committee shared information about simulator usage for training purposes among American air carriers.

The remaining two CTOs, Harris' User Exchange (HARUE) and the American Institute of Aeronautics and Astronautics' Working Group on Simulation Facilities (AIAAWGSF) are isolated from the other CTOs in this sample. In particular, AIAAWGSF was composed primarily of researchers and defense contractors; their understanding of flight simulation systems differed from that of the commercial users and regulators.

Era of Incremental Change

Taking Figure A-1 as a baseline, examine the transition in network structure after the emergence of the dominant design in 1980. Figure A-2 displays the aggregate network structure of the CTO community during the era of incremental change from 1981-1986. CTOs newly formed during the era of incremental change are denoted by italicized type. First, notice that the number of CTOs in existence more than doubles during this era, from 7 to 15. CTOs are proliferating even during the era of incremental change, yet none of the newly-formed CTOs are key CTOs.

Despite this proliferation of CTOs, we see that the overarching structure of the CTO cliques has remained consistent. In Figure A-2, new, enlarged cliques are denoted by dotted circles. Recall that the major clique from the first era of ferment was composed of three CTOs linked by common air carrier representatives (the Federal Aviation Administration's Advanced Simulation Plan Working Group (FAAASP), the International Air Transport Association's Flight Simulation Technical Subcommittee (IATAFSTC) and Data Pack Exchange Group (IATADPX)). This clique has retained its integrity during the era of incremental change. Recall also that the other four CTOs existing before the dominant design did not form cliques, but existed independently. Now, two of these four isolates have been joined by new CTOs. Thus, ATLAS now is in a clique with ARINC's Systems Architecture Integration Committee (ARINCSAI) and IATA's ARINC Subcommittee (IATAARIN), and ATATRAIN now is in a clique with the Wind Shear Working Group (WSWG). In other words, these two isolates spawned offspring CTOs: members already participating in the established CTOs became active under another umbrella. For example, several members of the ATA Training Committee (user airlines) formed the Wind Shear Working Group to experiment with approaches for wind shear training; they invited limited representatives of simulator and aircraft manufacturers to join them, increasingly interconnecting different constituents in the community. Rather than maintain all activities under the direction of the Training Committee, the Wind Shear Working Group was "spun off". Similar dynamics occurred with the ATLAS/ARINCSAI/IATAARIN clique. Additionally, the AIAA Working Group for Simulation Facilities changed its name to the AIAA Flight Simulation Technical Committee.

One new clique and two new islands also developed during the era of incremental change. Two user groups dedicated to information sharing, Rediffusion's Simulator User Group (REDSU) and Gould's Working Group (GOULDWG), form the new clique. The rise of a standardized full flight simulator design enabled the transmission of common information and the sharing of common concerns among multiple users of these systems. At the same time, the Simulator Sickness Working Group (SSWG) and the FAA's Helicopter Standards Group (FAAHS) are isolates. The SSWG was populated by researchers, and the FAAHS utilized some established regulators, but different user and manufacturing clienteles.

Second Era of Ferment

Contrast this transition after the dominant design in 1980 to the subsequent transition after the technological discontinuity in 1987. Figure A-3 displays the transition from the network structure of the era of incremental change to that of the second era of ferment from 1987 to 1992, using the same conventions as Figure A-2. Due to the complexity of the figure, weak common membership links are not displayed. During this era, CTOs continue to proliferate, growing in number from 15 to 24 (12 CTOs founded, 3 of which are key, and 3 CTOs disbanded). This time, however, membership has increased dramatically, from 22 to 43 members (22 individuals entering and 1 individual leaving). After the emergence of the technological discontinuity, common membership ties between CTOs have been dramatically altered. Previously existing cliques have fragmented and recombined as changes in memberships and an influx of new community members have reoriented network relationships.

Fragmentation. All five of the original cliques, elaborated during the era of incremental change, have been decimated by changing membership ties and the dissolution of some CTOs. Consider first the initial clique formed during the first era of ferment and maintained during the era of incremental change. This clique, containing the Federal Aviation Administration's Advanced Simulation Plan Working Group (FAAASP), the International Air Transport Association's Flight Simulation Technical Subcommittee (IATAFSTC) and Data Pack Exchange Group (IATADPX) has split in two. While IATAFSTC and IATADPX have retained common membership ties due to their trade association sponsorship, FAAASP has reduced ties to the other two CTOs, reflecting its increasingly diverse membership. Similarly, the clique previously containing the ATLAS consortium, ARINC's Systems Architecture Integration Committee (ARINCSAI) and IATA's ARINC Subcommittee (IATAARIN) has fragmented. ATLAS has split from IATAARIN, and ARINCSAI no longer has members from the community.

Other cliques in the community have fragmented or vanished as well. The clique containing the Air Transport Association's Training Committee (ATATRAIN) and the Wind Shear Working Group (WSWG) clique has split apart. The Harris' User Exchange (HARUE) no longer appears because flight simulation community members no longer populate HARUE.

Recombination. The set of fragments have recombined into other cliques, supported by the entry of new CTOs. Figure A-4 displays a streamlined representation of the new community structure during the second era of ferment, including weak common membership links. Three fragments (the FAA's Advanced Simulation Plan Working Group (FAAASP), the AIAA's Flight Simulation Training Committee (AIAAFSTC), and the FAA's Helicopter Standards Working Group (FAAHS)) have formed a clique, joined by two new CTOs, the FAA's Advanced Flight Training Device Qualification Working Group (FAAAFTQ) and the Society of Aeronautical Engineers' Simulation Committee (SAESC). While common membership between cliques was composed primarily of users during the two earlier eras, the common members that bind these CTOs into a clique are regulators. In short, this clique represent a “New Guard” which supports the flight training device-based approaches to simulation and training.

The other large clique (the “Old Guard”) represents the more traditional full flight simulation-based approaches to simulation and training. Three incumbent CTO's, the ATLAS consortium, IATA's Flight Simulation Technical Committee, and IATA's Data Pack Exchange Committee, are joined by the Royal Aeronautical Society's International Simulator Standards Working Group and the Joint Aviation Authority's Simulator Standards Working Group. The membership bonds between these CTOs are primarily users; these groups are attempting to propagate, extend, and standardize the Zero Flight Time approaches internationally.

Notice that the key CTOs are no longer concentrated in one dominant clique, splitting amongst the two Guards and some weakly tied segments. In addition, weak links have propagated, as would be expected with more members and more CTOs in the community. Indeed, most of the new CTOs are weakly linked to either the Old or New Guard, creating "spokes" of support around each of the Guards. In particular, notice that the two key CTOs not included in the Guards (the Air Transport Association's Training Group (ATATRAIN) and their Simulator Technical Issues Group (ATASTIG)) are weakly linked to both Guards as well as to each other.

FIGURE A-1

COMMUNITY STRUCTURE

FIRST ERA OF FERMENT

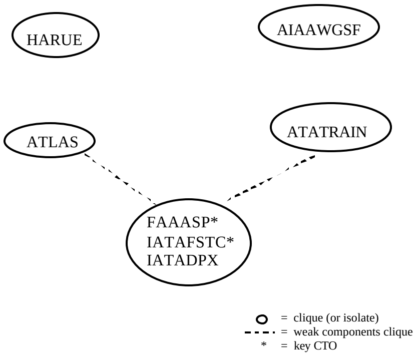


FIGURE A-2

COMMUNITY STRUCTURE

ERA OF INCREMENTAL CHANGE

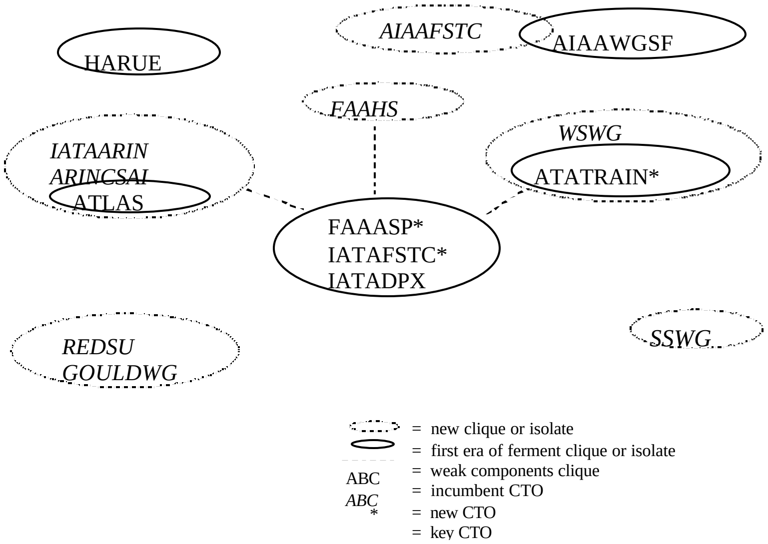


FIGURE A-3

COMMUNITY STRUCTURE

SECOND ERA OF FERMENT

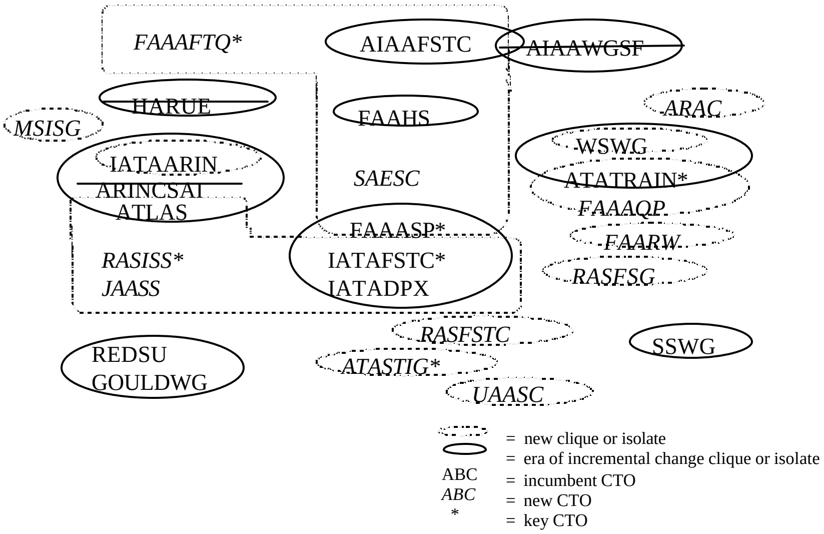


FIGURE A-4

SIMPLIFIED COMMUNITY STRUCTURE

SECOND ERA OF FERMENT