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Beyond electronic disintermediation through multi-agent systems

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Keywords

Business process re-engineering, Expert systems, Information systems, Supply chain management

Abstract

Supply chain management represents a critical competency in today's global business environment and has been the focus of considerable, but mixed, information systems research. The research described in this paper builds on work in multi-agent systems to argue that intelligent agents offer excellent potential and capability for supply chain management, and contributes to discussion and theory pertaining to electronic markets and supply chain disintermediation. Argues that the knowledge associated with intermediation work represents a key mediating variable between disintermediating technology and supply chain efficacy and discusses how intelligent agent technology can be employed to both intermediate and disintermediate the supply chain, attaining the cost and cycle-time benefits of disintermediation without the attendant loss of human knowledge and expertise. The paper outlines a number of implications for theory and practice in information systems, and it formalizes some important research questions through a contingency framework to help stimulate and guide future work along these lines.

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Supply chain management

Supply chain management (Porter and Millar, 1985) represents a critical competency in today's global business environment. Key supply chain processes such as procurement are now attaining strategic importance in the enterprise (Kearney, 1998), and supply chain management has become so important in many competitive arenas that corporate officers in major enterprises are now being promoted from purchasing departments (Stallkamp, 1997), a rare occurrence just a few years ago. The military also realizes the importance of supply chain management. Recently, the Secretary of Defense set forth a change-oriented strategic plan entitled "Leading Change in a New Era" (Cohen, 1997), in which he acknowledges that the supply chain (especially procurement and logistics) now limits fleet and battlefield information, mobility and speed.

Not only are supply chain managers responsible for back-office functions such as purchasing, order fulfillment and logistics, procurement executives are increasingly called upon to arrange and manage strategic partnerships, joint ventures, long-term sourcing agreements and other "non-equity arrangements" for inter-firm supply chain integration (Monczka *et al.*, 1998). Even the term supply chain is expanding in breadth to reflect its increasing scope and importance in the enterprise (Mabert and Venkataramanan, 1998). Although many researchers (Davis, 1993; Lee and Billington, 1995; Mabert and Venkataramanan, 1998; Porter, 1985; Swaminathan *et al.*, 1998) maintain a relatively narrow focus on supply chain process activities, Monczka *et al.* (1998) and others (Gebauer *et al.*, 1998; Kambil, 1997; Nissen, 1997) now concentrate on inter-organizational relationships between enterprise buyers and sellers, emphasizing commercial exchanges of goods, services, information and money. Indeed, the distinction is blurring between supply chain management and commerce through business-to-business markets, and many important principles and trends also apply to consumer markets as well. In this broader context of commercial exchange, supply chain management has been the focus of considerable, but mixed, information systems (IS) research.

One important stream of such IS research addresses the role and future of supply chain and market intermediaries. Intermediaries

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(e.g. brokers, agents, market makers, purchasing departments, distributors) play a number of important roles, including aggregation, trust, facilitation and matching (Bailey and Bakos, 1997). With the growing network connectivity and functionality enabled by information technology (IT), many researchers hypothesize a trend toward disintermediation (Gellman, 1996), whereby buyers and sellers are able to find one another, transact business and coordinate supply chain activities without the services of intermediaries. Davenport (1993, pp. 50-5) stresses this disintermediation effect in terms of opportunities for process innovation (e.g. cost and cycle time reduction):

> It is becoming increasingly clear in many industries that human intermediaries are inefficient for passing information between parties, particularly for relatively structured transactions such as stock brokerage, parts locating, and even finding a home.

Malone *et al.* (1987) go further, predicting IT will reduce the need for vertical integration and lead to increasing use of markets, as opposed to hierarchies (Williamson, 1985), for inter-firm supply chain coordination. Clemons *et al.* (1993) appear to agree in part, indicating that IT can be used to lower inter-organizational coordination costs without increasing transaction risk. In the "move to the middle hypothesis," they argue that firms will increasingly rely on markets to reduce vertical integration (e.g. through outsourcing). Bakos (1997) adds that electronic markets can dramatically reduce buyer search costs. With product and pricing information increasingly available electronically, potential buyers of goods and services can often make faster, lower-cost, better-informed purchasing decisions. And this class of IT can obviate the need for many intermediaries, particularly those functioning as information repositories and brokers. Bakos further argues that such disintermediation through "friction free markets" (Bakos, 1998) can also increase market efficiency for differentiated products:

> . . . an electronic market system in a differentiated market is likely to promote price competition and reduce the market power of sellers. It may thus create a net welfare gain by lowering the search cost of buyers and also enabling them to locate products better matching their needs.

One can now observe many IT-based supply chain practices (e.g. just-in-time deliveries, supplier inventory management) and enabling technologies (e.g. electronic data interchange (EDI), electronic catalogs, virtual malls and storefronts, intranets/extranets) with functionalities and usage patterns that support disintermediation hypotheses and arguments. For instance, EDI (Sokol, 1996) automates much of the creation, transmission and processing associated with routine business forms (e.g. purchase orders, invoices, payments). And the Internet is noted as offering good potential to "revolutionize procurement" and related commercial activities (Gebauer *et al.*, 1998), as intranet/extranet-based workflow systems (Ariba, 1999; Ironside, 1999) now enable users in the enterprise (e.g. in engineering, marketing, manufacturing organizations) to purchase products and services directly from vendors. This technological innovation enables non-procurement professionals to bypass the purchasing department, which functions as an internal intermediary in most large enterprises. And some commercial Web applications are now being used in lieu of brokers (E-Trade, 1999), agents (Southwest, 1999), market makers (CommerceOne, 1999) and other external intermediaries.

However, not all intermediaries are alike, and the mixed IS literature suggests that disintermediation – for example through electronic markets and other disintermediating IT – does not necessarily enhance supply chain efficacy. This provides the basis for a more tempered view toward disintermediation and raises the question of which contingency factors, if any, contribute to enhanced supply chain efficacy through electronic disintermediation. Bakos (1991, pp. 307-8) appears to support this tempered view, as the value-added role (e.g. through aggregation) and economic viability (e.g. through economies of scope) of "information intermediaries" is discussed. Bakos also makes the distinction between electronic markets for commodity and differentiated products, which represents a key factor for electronic disintermediation.

Bailey and Bakos (1997) further explore the value-added nature of various intermediation roles by investigating a number of contemporary examples of aggregation (e.g. digital content bundling), trust (e.g. value-added network), facilitation (e.g. information intermediaries) and matching (e.g. online product and pricing information) services. Their results are mixed with respect to trends toward intermediation or disintermediation in IT-enabled supply chains and markets. On the one hand, for example, despite "nonlinear pricing" (e.g. through availability of volume-purchase discounts) in the retail and automobile industries – and a technical capability to "self organize in electronic communities that have [increased] bargaining power in dealing with suppliers" – they indicate that customers are able to obtain better prices by "working directly with suppliers" (Bailey and Bakos, 1997, p. 14). Alternatively, with respect to an intermediary's buyer-seller matching service, they indicate "the overwhelming abundance of information offered by Internet-based market infrastructures may *increase* the need for intermediaries" (p. 16, emphasis added). Anyone who has ever used a Web-search engine is likely to relate to this information-overload phenomenon.

Interestingly, these mixed results are also consistent with the "move to the middle hypothesis," as Clemons *et al.* (1993, p. 13) temper their outsourcing predictions above. Suggesting closer integration between a smaller number of customers and suppliers along the supply chain, they refer to this latter effect as "a move away from the market to intermediate governance structures." Here, Clemons *et al.* are quite distinct from the "electronic markets hypothesis" (Malone *et al.*, 1987). Although such intermediate governance structures do not constitute strict vertical integration through equity ownership, they reflect a relatively stable, enduring relationship between customers and suppliers (Jarillo, 1988). And one can argue that the same kinds of non-market governance mechanisms discussed by Williamson (1985) are simply being extended across organizational boundaries, in essence "vertical" integration beyond the ownership of a single firm (e.g. along the supply chain).

Such inter-firm integration is consistent with the kinds of strategic partnerships, joint ventures, long-term sourcing agreements and other "non-equity arrangements" from above (Monczka *et al.*, 1998), which are employed to lower inter-organizational transaction costs without market mechanisms. This discussion suggests that the use of disintermediating IT, even with its potential for process innovation and to reduce search and coordination costs, does not necessarily imply a shift to market coordinating mechanisms or even a strict preference for disintermediation. Rather, many of the same "disintermediating" technologies are actually employed to integrate firms along the supply chain more closely, often through existing internal and external intermediaries.

Clemons and Weber (1997) take this suggestion still further, arguing that electronic disintermediation is even inferior in some respects to human intermediation. For instance, electronic disintermediation of securities pricing and market making eliminates important signals of risk associated with some trades. They assert that the human intermediary possesses knowledge and experience that enable better risk assessments associated with securities, which the intermediaries use to price trades more effectively on the basis of risk. The role of such intermediaries' knowledge and experience suggests some classes of commercial exchanges can be difficult to emulate or replace through extant IT. Thus, the nature of an intermediary's work may represent an important mediating variable between disintermediating technology and supply chain efficacy. If so, this could provide the basis of a contingency structure associated with supply chain disintermediation. Aside from distinguishing between electronic disintermediation in commodity and differentiated product markets, such a structure is relatively unexplored in the information systems literature.

The pervasive existence of procurement organizations, as internal intermediaries in most corporations, government agencies and other major enterprises, further highlights the point. Many specialists in procurement organizations acquire detailed knowledge and experience with specific products, firms, markets and industries. They spend considerable time in professional careers becoming intimately familiar with product characteristics, firm capabilities, market dynamics and industry trends to make purchasing decisions based on important factors in addition to price (Nissen *et al.*, 1998). These kinds of non-price factors often require judgment and expertise to assess, and information pertaining to such factors can be difficult to acquire or develop without detailed knowledge and experience (Reddy, 1998). Bailey and Bakos (1997) also note this knowledge factor in the context of intermediaries' buyer-seller matching services.

Moreover, although cost (e.g. product cost, transaction cost) is nearly always important in purchasing decisions, the purchase price represents only one part of the total cost of ownership or life cycle cost associated with a product (DoD 5000, 1996). Other critical factors – such as a product's technical performance, reliability and maintainability, along with a seller's history, willingness and capability for providing customer support – can be more important decision attributes than purchase price in many cases. This is particularly the case with mission-critical systems, as is noted in the literature on outsourcing (Aubert *et al.*, 1998; Choudhurry *et al.*, 1995; Cross, 1995; Duncan, 1998; Earl, 1996; Fabris, 1997). As above, information pertaining to such critical non-price factors can be very difficult to obtain without detailed knowledge and experience, and we know of no extant disintermediating technology that is able to emulate or replace human expertise and address this difficulty.

Procurement intermediaries, internal and external, also perform a valuable function by shielding other professionals (e.g. in engineering, marketing, manufacturing organizations) from the myriad policies, procedures, laws, rules and customs that govern corporate procurement in many industries and economic sectors. Most managers are likely to prefer their engineers to spend time on engineering work, not developing expertise in procurement. The same holds true for other functions (e.g. marketing, sales, manufacturing, product support) in the organization. Indeed, the requirement for specialization in this area represents a principal reason for the pervasive existence of procurement organizations in the first place.

Thus, we find some tension in the literature between benefits of electronic disintermediation, on the one hand, and the value-added services provided by intermediaries on the other. And we note mixed results of IT-enabled disintermediation through markets, as one trend, and closer inter-firm integration, using intermediate coordinating mechanisms similar to those employed in the hierarchy, as another. Moreover, due to knowledge work associated with intermediation, the nature of an intermediary's work may represent an important mediating variable between disintermediating technology and supply chain efficacy.

The research described in this paper builds on work by Barbuceanu and Fox (1993) and others (Collins *et al.*, 1998; Gini and Boddy, 1998; Mehra and Nissen, 1998; Nissen and Mehra, 1998; Rodriguez-Aguilar *et al.*, 1998; Walsh *et al.*, 1998; Wurman *et al.*, 1998) to argue that intelligent agents offer excellent potential and capability for supply chain management. We argue that the knowledge associated with intermediation work represents a key mediating variable between disintermediating technology and supply chain efficacy. And we discuss how intelligent agent technology can be employed to both intermediate and disintermediate the supply chain, attaining the cost and cycle-time benefits of disintermediation without the attendant loss of human knowledge and expertise.

Specifically, through the capability to formalize and embed domain-specific knowledge and market-specific expertise in multi-agent systems, this emerging technology offers potential to substitute federations of intelligent agents for many knowledgeable and experienced, internal and external intermediaries now employed along enterprise supply chains, while still taking advantage of electronic disintermediation. As such, it may provide many of the same kinds of value-added services expected from human and organizational intermediaries, but without the attendant cost and time associated with labor and "middlemen." This is the concept *virtual supply chain re-intermediation*. First, one electronically disintermediates the supply chain through IT. Then, to make up for lost knowledge and experience, one re-intermediates, virtually, with a federation of intelligent agents (i.e. a multi-agent system).

This research contributes to discussion pertaining to electronic markets and supply chain disintermediation, with the objective of extending theory through the concept of virtual supply chain re-intermediation. In the balance of the paper, we first provide a high-level overview of extant intelligent agent technology and then draw from the agents literature to discuss key agent capabilities and limitations with respect to supply chain management. Although these sections address intelligent agent technology and draw from computational research on multi-agent systems, the discussion is presented at a relatively high level, oriented toward the knowledgeable IS researcher and practitioner who may not have detailed expertise in agent design and development. This technological discussion is important to gain an appreciation for both the capabilities and limitations of intelligent agent technology and to understand the potential of virtual supply chain re-intermediation. We build upon this discussion to propose a contingency structure associated with electronic disintermediation. This contingency structure is consistent with some aspects of existing disintermediation theory, but it begins to depart from and extend to current research and thinking by differentiating between cases in which electronic disintermediation is and is not expected to enhance supply chain efficacy. It also balances the capabilities and limitations of intelligent agent technology to highlight both potential and difficulties associated with virtual supply chain re-intermediation. And it distinguishes situations calling for virtual re-intermediation (e.g. via multi-agent systems) from those more appropriate for continued human intermediation (i.e. through people and organizations). The paper thus outlines a number of implications for theory and practice in information systems. And it formalizes important research questions through a contingency framework to help stimulate and guide future work along these lines.

Multi-agent systems

Work on intelligent agents derives from research in artificial intelligence, distributed computing, software engineering and other computational disciplines (Guttman *et al.*, 1998; Jennings *et al.*, 1998). Software agents are referred to as "intelligent" when they possess knowledge (e.g. in the form of rules and facts) to autonomously make decisions and perform tasks on behalf of their principals. Accordingly, agents can be classified as textbook knowledge-based systems (KBS) (Turban and Aronson, 1998) and hence are similar to familiar expert systems in many respects. One key difference is that individual agents are generally quite small and limited in terms of knowledge and capability, with respect to a traditional expert system. Other key differences stem from agent mobility and the ability of agents to collaborate through federations to solve problems. In contrast, expert systems typically operate on a single processor and as standalone entities. Key differences between agents, expert systems and other familiar information technologies are discussed further below.

The term multi-agent system as used here applies to coordinated problem solving through a federation of intelligent agents. Where only a single agent is involved with problem solving, or multiple agents solve problems independently, we refer to these as single-agent systems or simply intelligent agents. Despite the novelty of the present investigation, work in the area of multi-agent systems has been ongoing for some time, and it addresses a broad array of applications. Indeed, one need not research too far back in the literature to identify a plethora of agent examples – so many that any attempt to review them, even briefly, would constitute a journal-length paper in and of itself (Bradshaw, 1997; Huhns and Singh, 1998; O'Hare and Jennings, 1996; Weib, 1998; Wooldridge and Jennings, 1995). In this section, we provide a high-level overview of extant intelligent agent technology. We employ a classification system to structure the discussion and categorize diverse agent applications and extend a technological framework to compare agent technology with other, more familiar classes of IT. This provides necessary background information to appreciate the subsequent summary of key agent capabilities and limitations and to understand the potential of virtual supply chain re-intermediation.

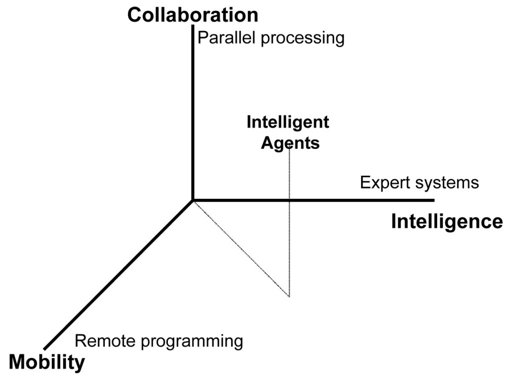
Agent classification and comparison

To gain perspective of the many different agents developed to date, we draw from Nissen (2000) to group extant agent applications – both single- and multi-agent systems – into four classes:
(1) information filtering agents;
(2) information retrieval agents;
(3) advisory agents, and
(4) performative agents.

Briefly, most information filtering agents are focused on tasks such as screening user-input preferences for e-mail (Maes, 1994; Malone *et al.*, 1997), network news groups (Sycara and Zeng, 1996), frequently asked questions (Whitehead, 1994) and arbitrary text (Verity, 1997). Information retrieval agents address problems associated with collecting information pertaining to commodities such as compact disks (Krulwich, 1996) and computer equipment (uVision, 1998), in addition to services such as advertising (PriceWatch, 1997) and insurance (Insurance, 1997). We also include the ubiquitous Web indexing robots in this class (Etzioni and Weld, 1995; Hsinchun *et al.*, 1998) along with Web-based agents for report writing (Amulet, 1997), publishing (InterAp, 1995) and assisted browsing (Burke *et al.*, 1997). Agents for technical information delivery (Bradshaw *et al.*, 1997) and information gathering (Knobloch and Ambite, 1997) are not Web-based *per se*, but they perform a similar function.

A third class of agents is oriented toward providing intelligent advice. Examples include recommendations for CDs (Maes, 1997), an electronic concierge (Etzioni and Weld, 1995), an agent "host" for college campus visits (Zeng and Sycara, 1995) and planning support for manufacturing systems (Maturana and Norrie, 1997). Agents for strategic planning support (Pinson *et al.*, 1997), software project coordination (Johar, 1997) and computer interface assistance (Ball *et al.*, 1997) are also grouped in this class, along with planned support for military reconnaissance (Bui *et al.*, 1996) and financial portfolio management (Sycara *et al.*, 1996). Performative agents in the fourth class are generally oriented toward functions such as business transactions and work performance. Examples include a marketspace (Rayport and Sviokla, 1994) for agent-to-agent transactions (Chavez and Maes, 1996), agent auction environments (Rodriguez-Aguilar *et al.*, 1998) and an agent system design for negotiation (Bui, 1996), in addition to performance of knowledge work such as automated scheduling (Sen, 1997; Walsh *et al.*, 1998), cooperative learning (Boy, 1997) and automated digital services (Mullen and Wellman, 1996). Interest is growing in the use of performative multi-agent systems for work along the enterprise supply chain (Collins *et al.*, 1998; Li and Williams, 1999; Shen *et al.*, 1999). And the arguments in this paper are motivated in particular by our own work with intelligent supply chain agents (Mehra and Nissen, 1998; Nissen and Mehra, 1998; Nissen, 2000). A high-level overview of these latter supply chain agents is presented in the Appendix for the interested reader.

Figure 1 Agent technological framework



Source: Adapted from Nissen (2000)

Agent technological framework

To further describe intelligent agents and differentiate them from other, more familiar classes of information technology, we integrate the agent-taxonomy work of Franklin and Graesser (1996) with a three-dimensional, agent-capability structure from Gilbert *et al.* (1995) to develop the agent technological framework presented in Figure 1. In this framework, we use the same intelligence and mobility dimensions developed by Gilbert *et al.* (1995) but substitute the new dimension collaboration in lieu of autonomy/agency. This follows the presumption of agent autonomy stressed by Franklin and Graesser. For purpose of discussion, and at some risk of over-generalization, we have annotated this three-dimensional space with one, relatively "pure" exemplar from each agent-capability dimension. For example, many expert system applications are quite extensive in terms of formalized, expert-level intelligence, but they are not traditionally designed as mobile software entities to operate on foreign hosts, nor do they generally collaborate with other expert systems to jointly solve problems. Similarly, remote programming of the sort enabled by Java, Telescript and Odyssey equip programs to execute on foreign machines, but these procedural applications are not generally endowed with the capability for intelligent inference, nor are they usually employed for collaborative processing. Likewise, parallel processing has an explicit focus on collaborative problem solving between multiple, parallel processors, but this problem solving is usually focused more on procedural processing than intelligent reasoning, and execution on foreign hosts is rarely envisioned. Clearly, exceptions exist for each class (e.g. distributed AI (Bond and Gasser, 1988), intelligent Java agents (Neuenhofen and Thompson, 1998), others), but these three exemplars should convey the basic concepts and capabilities associated with each dimension and help the reader compare and contrast intelligent agents with other, more familiar classes of IT.

Notice the annotation for intelligent agents in the figure. It occupies a notional position in the middle of this three-dimensional agent-capability space. This

suggests the capabilities of intelligent agents are not as extensive as those possessed by any of the three exemplars from above along any particular dimension. Yet none of the exemplars from above combines even two of these three capability dimensions associated with agent systems. This serves to enable a new set of powerful capabilities through mobile, collaborative performance of knowledge work activities, but it adds to the challenge of agent development work – particularly where intelligent problem solving must be coordinated among a federation of autonomous, mobile agents. Further, the dimensions of this agent technological framework can be useful to gain an appreciation for both agent supply chain capabilities and limitations.
This is important to understand the potential of virtual supply chain re-intermediation.

Agent supply chain capabilities and limitations

In this section, we outline the principal agent capabilities and limitations with respect to supply chain intermediation and disintermediation. We feel it is important not to characterize agents as elements of fantasy or portray them in the distant computational future. Thus, the discussion is grounded in the current agents literature and reflects technology available today (albeit predominantly still in the laboratory). As noted above, the discussion is presented at a relatively high level, oriented toward the knowledgeable IS researcher and practitioner who may not have detailed expertise in agent design and development.

For each aspect of agent supply chain capabilities and limitations below, we first draw from the literature to be informed by agent theory and practice. We then discuss supply chain implications, provide a concrete supply chain instance and note an example of our corresponding experience with intelligent supply chain agents mentioned above. Examples from this latter agents experience base are not discussed in detail nor necessarily presented as exemplars of effective agent design or development. Rather, they are included to provide specific examples of how the theoretical and practical agent supply chain capabilities and limitations manifest themselves in at least one implemented multi-agent system.

Agent supply chain capabilities

Drawing from the agents literature, key agent supply chain capabilities derive from six sources:
(1) autonomous behavior;
(2) social conformance;
(3) individual flexibility;
(4) collaborative problem solving;
(5) network mobility; and
(6) distributed architecture.

These capabilities reflect the three agent-capability dimensions presented above – intelligence, mobility and collaboration – and are important to appreciate in the context of virtual supply chain re-intermediation. We outline each in turn.

Autonomous behavior

As noted above, software agents are referred to as “intelligent” when they possess knowledge (e.g. in the form of rules and facts) to autonomously make decisions and perform tasks on behalf of their principals (Franklin and Graesser, 1996; Jennings *et al.*, 1998). And we indicated that this qualifies agents as textbook knowledge-based systems (Turban and Aronson, 1998). From the agent-capability discussion above, intelligence represents the primary differentiator between an agent-based approach and other contemporary technologies employed for supply chain intermediation/ disintermediation or electronic markets (Guttman *et al.*, 1998; Nissen, 2000). Because agents can store, process and act on domain knowledge, they offer a capability to emulate or possibly even replace the kinds of detailed knowledge and experience noted above as important for effective knowledge work associated with procurement and other supply chain intermediation activities. This capability and role is similar to that possessed and played by expert systems for two decades.

For instance, agents can be developed to acquire the same kinds of specialized knowledge about products, firms, markets and industries possessed by (human) professionals in the procurement organization. Indeed, in a highly-parallel computational approach, each agent instance can be created and sent out to specialize in one particular product, firm, market or industry, conceivably with dozens, hundreds or thousands of such agent specialists working together in a supply chain federation to augment or supplement the kind of knowledge and expertise currently employed by human intermediaries, internal or external.

As an example, the supply chain agents developed by Nissen and Mehra (1998) specialize in the procurement and order fulfillment of commercial off-the-shelf (COTS) software.

Social conformance

Social conformance represents an important topic in agents research (Gasser, 1998), for most multi-agent systems are expected to adhere to the same set of social and organizational rules of behavior as the people they represent, augment and emulate in the enterprise. In the supply chain, agent knowledge can be employed for conformance to the myriad policies, procedures, laws, rules and customs that govern corporate procurement in many industries and economic sectors (Nissen and Mehra, 1998).

For instance, supply chain personnel at IBM probably have a different set of policies and procedures to follow than their counterparts at Wal-Mart, the Navy, University of California or local church. Yet considerable commonality is likely to exist between procurement processes of even such diverse enterprises. Through rules and like mechanisms for knowledge formalization, the policies and procedures of each particular enterprise can be captured and used to specialize agents in a socially-conforming manner (e.g. adhering to corporate policies and procedures for procurement). But because good object-oriented techniques (e.g. abstraction, inheritance) are employed to design many agent applications today (Erickson, 1997; Jennings *et al.*, 1998), such knowledge need only be specified and formalized once, at the class level, after which it is automatically inherited to control the behaviors of each agent instance created. This allows for great scalability across even diverse enterprises. In the case of our software supply chain agents (Mehra and Nissen, 1998), knowledge at the process level is formalized only once – for the user, procurement and vendor agent classes. Each of the many specific agent instances created from its parent class then automatically inherits the requisite knowledge and exhibits the appropriate behaviors in the enterprise.

Individual flexibility

Agent flexibility represents a fundamental design goal for multi-agent systems (Malone *et al.*, 1997; Jennings *et al.*, 1998). Like the capabilities above, agent flexibility is enabled by formalized knowledge. In the supply chain, each agent can be specialized, tailored and parameterized to reflect the job duties, knowledge and preferences of a specific individual in the organization (Nissen, 2000). And each individual in the organization can instantiate a multitude of agents tailored to reflect his/her individual preferences and activated to serve only him/her.

For instance, one principal's agents, say specialized to monitor price and performance changes of computer memory chips, may differ from another's at the instance level. Yet they may be created from the same class, exhibit the same general behaviors, communicate using common message protocols and conform to the same set of organizational rules. As an example from our agents' work, the author is on a budget and has very price-sensitive software supply chain agents, whereas yours may be tailored instead to seek out the latest technological advances or search for the highest performance levels. Still, both sets of agents – yours and the author's – are instantiated from the same parent class and reflect a common design.

Collaborative problem solving

Also noted above is the collaborative nature of agents in a federation. Collaborative capability is what constitutes a multi-agent system (Bradshaw, 1997; Jennings *et al.*, 1998) and helps differentiate this class of information technology from traditional, object-oriented client-server applications, for example. In the supply chain context, because each specific agent is relatively small and limited in terms of knowledge and capability, it is relatively easy for various users to develop, specify and tailor agent instances to individual jobs and preferences. Yet through collaboration, agents in a federation are capable of solving difficult problems and performing useful process activities along the supply chain (Barbuceanu and Fox, 1993; Shen *et al.*, 1999).

For instance, nearly all agents communicate through messages (Shoham, 1997), but a wide variety of approaches to multi-agent coordination and collaboration have been proposed (Cohen and Levesque, 1991; Jennings *et al.*, 1998; Lesser, 1998). These range (in order of difficulty) from strict hierarchies, through federations of specialized, homogeneous agents from common classes, to third-party, heterogeneous agents that interact opportunistically, with no pre-established mechanism for collaboration. As an example drawing from Nissen and Mehra (1998), we note above how one agent class is specifically designed to represent an enterprise user (e.g. in an engineering, marketing, manufacturing organization), while another performs services of a procurement department intermediary and a third acts on behalf of one or more vendors along the supply chain. These agents coordinate their activities through job specialization and division of labor – mirroring the manner in which people in the enterprise coordinate – using messages to communicate and collaborating through information sharing to perform assigned supply chain activities in a timely manner.

Network mobility
We also noted agents are network mobile. Some researchers view mobility as a necessary condition for labeling a software application as an "agent" (Nwana, 1996; White, 1997). And agents can be designed to be persistent, as well as autonomous (Bradshaw, 1997). Once assigned, such agents can faithfully monitor a designated supply chain site, for example, until its objective is satisfied or it is recalled, timed-out or destroyed by the principal. Because supply chains are often distributed, sometimes both around the world and through time, network mobility endows agents with a powerful capability for information discovery, monitoring and collaboration.

For instance, supply chain agents can begin performing some steps of a task at one (network) location, say on a specific user's workstation (e.g. an engineer in California), and travel to perform subsequent steps on one or more other machines (e.g. in the procurement department, vendor organization), in either the same or different physical locations. This enables agents to go to where the necessary data, information and knowledge reside, collaborate with other agents in their native environments and "sit on" or monitor (Moukas and Maes, 1998) one or more specific physical sites or virtual addresses (e.g. company product site, information source, news channel, market index). As an example from Nissen and Mehra (1998), one set of software supply chain agents specializes in commercial expert system development software from a particular vendor on the east coast. These agents are specifically tailored to reflect the author's software preferences, conform to our organization's procurement policies and monitor this specific vendor's communications along the supply chain.

Distributed architecture
The nature of a multi-agent system is inherently distributed by architectural design (Jennings *et al.*, 1998). We note above how each agent instance is relatively limited, but that agents can collaboratively solve problems, are socially conforming and tailorable to the level of an individual in the organization. In the supply chain context, the distributed architecture implies it is relatively easy for various users in the enterprise to add or remove individual, specialized agent instances from a federation. And agents' processing loads can be distributed across a multitude of machines to promote scalability, without affecting their individual autonomy or ability to collaborate. Moreover, autonomous, network-mobile agents can conceivably move to take advantage of under-utilized computational resources.

For instance, the same, parent agent classes can be used to perform a set of commercial process activities regardless of whether used to instantiate dozens, hundreds or thousands of individual agent instances in a federation. This distributed nature of multi-agent systems makes for a highly-scalable architecture, which offers good promise for enterprise applications. As an example from Nissen (2000), our software supply chain federation has been used with over 100, individually-specified agent instances.

Agent supply chain limitations

Drawing again from the agents literature, key agent supply chain limitations derive from four factors:
(1) knowledge engineering;
(2) design inexperience;
(3) message congestion; and
(4) third-party collaboration.

These limitations serve to temper claims about inherent superiority of agent technology and are important to appreciate in the context of virtual supply chain re-intermediation. We outline each in turn.

Knowledge engineering
Knowledge engineering, involving the capture and formalization of knowledge for use by a knowledge-based system (e.g. expert system, multi-agent system), has been the principal bottleneck to development of intelligent systems for decades (Russell and Norvig, 1995). In the supply chain context, it is essentially a boundary-spanning activity to link domain experts (e.g. in procurement, order fulfillment, logistics, other supply chain

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process) with software engineers skilled in KBS development (Turban and Aronson, 1998). Many problems can impair this activity.

For instance, a given domain expert many know nothing about KBS development, and the corresponding knowledge engineer may know even less about the supply chain domain, so communication can be difficult. This is particularly the case with multi-agent systems, because the technology is relatively new and unfamiliar to many people, certainly with respect to its expert systems technological counterpart. As an example from Mehra and Nissen (1998), our specialist in agent development originally knew very little about enterprise procurement, and procurement specialists in the enterprise had never heard of intelligent agents. The author helped span these roles to develop the multi-agent system application.

Design inexperience

Despite the plethora of agent applications noted in the previous section, agent development remains a nascent discipline, and little design guidance specific to agent development exists at present (Erickson, 1997; Jennings *et al.*, 1998). Even though most agent applications are implemented using object-oriented techniques and expert system development methods (Wooldridge, 1998), for which considerable guidance and expertise exists, the autonomous, distributed, collaborative nature of multi-agent systems in the supply chain presents design challenges not encountered in most applications that comprise this experience base. Again, this point is underscored by the notional position of intelligent agents technology in the middle of the three-dimensional, agent-capability framework discussed above.

For instance, researchers are still investigating basic questions pertaining to agent architectures (Bradshaw *et al.*, 1997), communication languages and protocols (Finin *et al.*, 1997), ontologies and representational formalisms (Genesereth, 1997; Gruber, 1992), developmental techniques (Mehra and Nissen, 1998), testing and validation (Nissen and Mehra, 1998) and others. Further, as an example from the software supply chain agent federation (Nissen and Mehra, 1998), this multi-agent system is designed to share work with people in an enterprise supply chain; that is, agents perform some process activities and people perform others. Little guidance (Hudson, 1998) exists for determining which process activities should be delegated to agents and which should be retained by people, or even on what factors and contingencies such delegation decisions should be made. Since agents are intended to act autonomously in the enterprise, these decisions must necessarily be made before agent design can begin.

Message congestion

Agent autonomy and collaboration represents a mixed blessing. On the one hand and as noted above, multi-agent systems are flexible to the level of each individual in the organization, and such systems are very robust to specific agent instances being added or removed from a federation. But agents communicate through messages and consume computational resources (Shoham, 1997). In the supply chain context, the more agents that comprise a federation and the more intensive their need for collaboration, the higher the frequency and number of messages sent between them.

For instance, when procurement agents must communicate with multiple (*m*) vendor counterparts (e.g. representing two or more potential suppliers), agent communications increase exponentially with the number of agents (*n*) in a federation (i.e. n^m). As an example from our work (Nissen, 2000), this can cause congestion in a multi-agent system, not only because of communication bandwidth and computer processing limitations, but agents may also have to spend time and inference determining which messages (e.g. requests for quotation, quotations, orders) are even relevant.

Third-party collaboration

Third party collaboration remains a difficult problem in agents research (Bradshaw, 1997). And it compounds the difficulties outlined above. Different designers may employ incompatible agent architectures, ontologies, representational formalisms, communication languages and protocols that limit the ability of such heterogeneous agents to even communicate, much less coordinate their activities and collaborate to solve problems and perform tasks. In the supply chain context, until this problem is addressed, multi-agent systems are largely limited to federations designed and developed as part of a single supply chain application. This constrains the scalability of multi-agent systems beyond single applications.

For instance, a supply chain federation – predicated on a homogeneous-agent design –

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may be able to extend no further than a single customer enterprise and its associated trading partners. Should a new trading partner decide to join the federation, it could only do so by utilizing homogeneous agents from the same design. As an example from the software supply chain agent federation noted above (Nissen and Mehra, 1998), the enterprise employs homogeneous agents from a common design to represent the user, procurement department and vendor. As a single design and system, the agents "know" one another's roles, "speak" the same language, follow common protocols and are able to effectively communicate, coordinate and collaborate along the supply chain. For this system to scale, the same agent classes must be used by each vendor at present. If some other vendors build their own classes of agents, and do not accommodate our design, chances of their collaborating effectively are slim. Notwithstanding advances in shared ontologies (e.g. ontolingua), representational formalisms (e.g. knowledge interchange format) and communication protocols (e.g. knowledge query manipulation language), this probably represents the greatest obstacle to scalability of multi-agent systems.

Summary

To summarize, agent supply chain capabilities derive from six sources:
(1) autonomous behavior;
(2) social conformance;
(3) individual flexibility;
(4) collaborative problem solving;
(5) network mobility; and
(6) distributed architecture.

These capabilities combine to enable a unique set of functionalities associated with multi-agent systems that supports autonomous decision making, procedurally-correct behaviors and automatic performance of knowledge work along the supply chain. However, four factors drive the primary agent supply chain limitations:
(1) knowledge engineering;
(2) design inexperience;
(3) message congestion; and
(4) third-party collaboration.

These limitations affect the ability to design, implement, operate and scale-up multi-agent system applications in the enterprise. Thus, multi-agent systems offer powerful new capabilities in terms of supply chain performance, but this nascent technology is not yet mature or well understood. And the potential of multi-agent systems to enhance supply chain efficacy is in no way unchecked. Further, agent capabilities and limitations determine to a large extent how far this relatively new class of information technology can take supply chain management beyond electronic disintermediation.

Beyond electronic disintermediation

In this section, we extend current discussion and theory beyond electronic disintermediation. In particular, we propose a disintermediation contingency structure and differentiate between cases in which electronic disintermediation is and is not expected to enhance supply chain efficacy. Drawing from discussion of agent capabilities and limitations, we use these cases to identify opportunities for virtual supply chain re-intermediation through multi-agent systems. Together, these arguments establish a basis for new IS understanding and practice pertaining to supply chain management.

As noted above, some tension exists in the literature between benefits of electronic disintermediation, on the one hand, and the value-added services provided by intermediaries on the other. And mixed results are noted with respect to IT-enabled disintermediation through markets, as one trend, and closer inter-firm integration using intermediate coordinating mechanisms similar to those employed in the hierarchy as another. Such tension and mixed results often signal the existence of some mediating variable, which has yet to be identified, able to explain the variation of results through a contingency structure (Mumford *et al.*, 1985). We also noted above the knowledge work associated with intermediation. Here we propose that the nature of an intermediary's work mediates the effect of electronic disintermediation on supply chain efficacy. Specifically, we draw from recent work in knowledge management (Davenport and Prusak, 1998; Hedlund, 1994; Ruggles, 1998; Teece, 1998) to distinguish data and information from knowledge and experience. Whereas the former data and information are generally explicit in an enterprise and easily stored and transferred electronically, the latter knowledge and experience are often tacit (Nonaka, 1994) and can be quite difficult to capture and distribute by computer (O'Leary, 1998). Key factors associated with supply chain participants are presented in Figure 2.

At a high level, three supply chain participants are shown in Figure 2; buyers, sellers, and intermediaries.. This model pertains to either internal (e.g. procurement departments) or external (e.g. market makers) intermediaries and can accommodate multiple levels of intermediation between buyers and sellers. Drawing from current electronic commerce models (Gebauer *et al.*, 1998; Kambil, 1997; Nissen, 1997), key attributes are listed below each supply chain participant. For instance, three attributes indicate the buyer has domain expertise (e.g. in engineering, marketing, manufacturing) and knows his or her procurement requirements and budgetary constraints. Similarly, three complementary attributes indicate the seller has product expertise and knows its sale terms and pricing information. Other attributes may also be important for commerce in general, but they are not primary in this discussion.

Figure 2 also shows important attributes for intermediation work. The first pertains to the nature of the product market and emphasizes the distinction noted above between that commodities and differentiated goods. In his classic article, Bakos (1991) indicates that commodity products (e.g. agricultural grain, gold bullion, government bonds) are fungible and essentially identical across all sellers. Accordingly, "a commodity product bought from different sellers can differ only in its price" (p. 299). In contrast, "the majority of markets are characterized by differentiated products ... because buyer preferences are heterogeneous" (p. 300). Buyers in differentiated markets need to consider both the price offered by a particular seller and the non-price characteristics of the product offering. This distinction between commodity and differentiated products represents a key factor discussed in current disintermediation theory. Yet Bakos (1991; 1997) argues that good opportunities exist for electronic disintermediation through IT in both commodity and differentiated product markets (i.e. not a contingency factor).

Figure 2 Key supply chain factors

Buyers	Intermediaries	Sellers
- domain expertise	- commodity or differentiated	- product expertise
- requirements	- data & information	- terms
- budget	- knowledge & experience	- prices

The present article extends current discussion and theory pertaining to disintermediation through introduction of the other intermediaries' attributes listed in the figure. These latter attributes pertain more to the nature of an intermediary's work than the products themselves or markets in which they are sold. In particular, we distinguish between intermediation work involving data and information from that requiring knowledge and expertise. The former pertains to clerical and information work supported by many extant information technologies (e.g. database management systems, transaction processing systems, decision support systems, intranets/extranets), in which data and information are processed and communicated. Here, we posit that data and information obtained from human and organizational intermediaries may offer good potential for direct access through extant disintermediation technologies. In contrast, the latter pertains to knowledge work supported by few extant information technologies (cf. expert systems), in which knowledge and expertise are distributed and employed. Here, we posit that knowledge and experience applied through human and organizational intermediaries may not be conducive to capture and distribution through extant disintermediation technologies.

The resulting disintermediation contingency structure is presented in Figure 3. This structure is depicted by a four-cell table formed by interaction between two disintermediation variables:

(1) nature of product market; and
(2) nature of intermediation.

Figure 3 Disintermediation contingency structure

Nature of Intermediation	Nature of Product Market: Commodity	Nature of Product Market: Differentiated
Work involves Data & information	Electronic disintermediation (conventional IT)	Electronic disintermediation (agents)
Work requires Knowledge & experience	Electronic re-intermediation (agents)	Electronic re-intermediation (agents) Human intermediation

We begin with the first, data and information row and commodity market column. Recall buyers of commodity products need consider only price information. Let us further qualify the discussion by assuming price information is available or can be determined with certainty or great assurance (e.g. commodity futures markets). Bakos (1991) argues that such price information is easily disseminated electronically. As depicted in the figure, cases marked by this cell of the contingency structure provide good opportunities for electronic disintermediation, through conventional classes of IT (e.g. databases, intranets, search engines).

The next cell in this data and information row pertains to differentiated products, in which both price and non-price product characteristics represent important buyer considerations. As above, let us further qualify the discussion by assuming price and product information is available. However, we also presume the non-price information (e.g. pertaining to product performance, reliability, support) is available but more difficult to obtain (e.g. in markets for computer hardware, software, residential homes). Price and non-price information for such products is easily disseminated electronically, once it is acquired. Bakos (1991) argues that such cases (e.g. as marked by this cell of the contingency structure) also provide good opportunities for electronic disintermediation. But a strong argument can be made that conventional IT is inadequate to acquire non-price information associated with differentiated products and services, unless a seller has gone to unusually great lengths (e.g. expressly entered and indexed such information in online catalogs). Alternatively, the capability of agents (e.g. to autonomously move across and search the network, employ intelligence to represent their users) may support electronic disintermediation, even for such differentiated products. This aspect of the contingency structure then begins to depart from current disintermediation theory.

The second, knowledge and experience row of the contingency structure further extends current research and thinking. This second row applies when the work of an intermediary requires considerable knowledge and experience. Examples include situations in which deep understanding of market forces and trends is required for informed purchase and sale decisions (e.g. possessed by some investment advisors and securities brokers); where detailed and local knowledge is required to assess the suitability of alternatives (e.g. concerning an unfamiliar hotel at a foreign resort); when the non-public reputation of potential vendors is important (e.g. when evaluating an unknown contractor, potential new business partner, Web-based vendor); with any number of experience goods (e.g. software, news, music) that require use by a prospective buyer to make an assessment; and others. In cases such as these, it is unlikely that a buyer will be able to acquire the necessary information without the assistance of an intermediary, particularly when the buyer lacks direct experience with a specific vendor, product or service.

In the case of commodities, an example pertains to risks associated with market making for securities (e.g. municipal bonds). As noted by Clemons and Weber (1997), knowledge and experience of an intermediary represent important factors for assessing risk and the associated cost of making a trade. Indeed, they indicate that electronically disintermediated supply chain performance can be inferior to that of human intermediation. Absent a human or organizational intermediary, to augment supply chain efficacy in such a case, the securities trader would need some other class of IT to make up for the lost knowledge and experience not captured by extant electronic trading systems. Drawing from the discussion above, these represent just the kinds of capabilities available through intelligent agent technology.

But note the different role played by agents here with respect to that above (i.e. for differentiated products). Whereas agents could effectively disintermediate markets for differentiated products (e.g. by autonomously and intelligently acquiring non-price product information), in this latter case, agents are proposed instead to re-intermediate the market, essentially replacing (or supporting) human intermediaries already in place. Such re-intermediation through multi-agent systems does not represent a well understood and researched concept in the current IS literature. And few practitioners are likely to understand either the availability or ramifications of this novel alternative at the present time.

The fourth cell involves cases in which buyers also consider non-price information. As above, this second row applies when the work of an intermediary requires considerable knowledge and experience. In the case of differentiated products, an example pertains

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to custom-developed software. As noted by Kemerer (1997) and others (Albrecht and Gaffney, 1983; Boehm, 1984; Scacchi and Boehm, 1998), it is very difficult to predict the cost (i.e. price) and capability (e.g. technical performance, reliability, maintainability) of unprecedented software. Even vendors' quoted software prices and capabilities are suspect (STSC, 1996). Developing reliable estimates for such price and non-price information requires an (internal or external) intermediary with considerable knowledge and expertise in the software domain. And given the wide variation in capability of software developers (SEI, 1999), one can argue that obtaining such reliable information also demands an (internal or external) intermediary with specific experience and familiarity with each particular software vendor. Absent a human or organizational intermediary to augment supply chain efficacy in such a case, the software manager would need some other class of IT to make up for the lost knowledge and experience not captured by extant electronic disintermediation systems. Again drawing from the discussion above, these represent just the kinds of capabilities available through intelligent agent technology.

This represents a second, contingent situation that would call for re-intermediation through multi-agent systems. Provided such multi-agent systems can be developed to perform at a level equal to or better than their human counterparts in an intermediation role, this represents a feasible choice. Alternatively, where the knowledge required for effective intermediation is too complex or difficult to obtain for incorporation into agents, the multi-agent system is unlikely to outperform human intermediaries. Thus, we show both re-intermediation through agents and intermediation through people as entries in this fourth cell of the table. In order to summarize this discussion, we add a third row to the contingency structure presented in Figure 4. Here, we further differentiate knowledge work of an intermediary on the basis of its complexity.

To reiterate from above, those cases in which price data and information can be obtained with certainty or great assurance are designated by the contingency structure as appropriate for electronic disintermediation, through conventional IT, for commodity products. Electronic disintermediation is also designated for differentiated products, but agent technology is likely to be required for acquisition of non-price data and information. In both of these cases, the nature of intermediation work centers around data and information, not knowledge.

Figure 4 Expanded disintermediation contingency structure

Nature of Intermediation	Nature of Product Market: Commodity	Nature of Product Market: Differentiated
Work involves Data & information	Electronic disintermediation (conventional IT)	Electronic disintermediation (agents)
Work requires simple knowledge & experience	Electronic re-intermediation (agents)	Electronic re-intermediation (agents)
Work requires complex knowledge & experience		Human intermediation

Alternatively, those cases that require deep intermediation knowledge and experience are designated by the contingency structure as inappropriate for electronic disintermediation, both for commodity and differentiated products. Rather, some form of intermediation is designated as appropriate. In the first case of commodity products, the contingency structure suggests re-intermediation by multi-agent systems as appropriate. And even in the case of differentiated products – provided the requisite intermediation knowledge is not too complex for acquisition and incorporation into agent systems – such virtual re-intermediation is similarly designated as appropriate. On the other hand, where such intermediation knowledge is complex or difficult to obtain, human intermediation is designated as the appropriate mode of supply chain operation.

Through this contingency structure, we add to the IS literature and enrich the discussion and theory pertaining to disintermediation. And this new structure provides a novel framework to help guide future research along these lines. We address some key elements associated with an agenda for such future research below.

Conclusions and future research

Supply chain management represents a critical competency in today's global business environment. And supply chain management has been the focus of considerable, but mixed, information systems research. We found some tension in the literature between benefits of electronic disintermediation, on the one hand, and the value-added services provided by intermediaries on the other. And we noted mixed results of IT-enabled disintermediation through markets, as one trend, and closer inter-firm integration using intermediate coordinating mechanisms similar to those employed in the hierarchy as another. Moreover, due to knowledge work associated with intermediation, we argued that the nature of an intermediary's work may represent an important mediating variable between disintermediating technology and supply chain efficacy. Aside from distinguishing between commodity and differentiated product markets, any corresponding contingency structure associated with supply chain disintermediation has been relatively unexplored in the information systems literature.

Based on an understanding of extant disintermediation and intelligent agent technologies, and consideration of key agent capabilities and limitations drawn from the agents literature, this paper has built on work by numerous researchers to argue that intelligent agents offer excellent potential and capability for supply chain management. Through the concept of virtual supply chain re-intermediation, we discussed how intelligent agent technology can be employed to both intermediate and disintermediate the supply chain, attaining the cost and cycle-time benefits of disintermediation without the attendant loss of human knowledge and expertise.

This investigation contributes to and extends discussion and theory by taking current research and thinking beyond electronic disintermediation. In particular, we proposed a disintermediation contingency structure and differentiated between cases in which electronic disintermediation is and is not expected to enhance supply chain efficacy. We then drew from discussion of agent capabilities and limitations to identify opportunities for virtual supply chain re-intermediation through multi-agent systems. Together, these arguments establish a basis for new IS understanding and practice pertaining to supply chain management. And it offers potential to open new lines of future research in this important area.

Future research addressing disintermediation theory has good potential along both theoretical and empirical lines. For example, theoretical work can challenge, reinforce and extend the present investigation, as the mediating variables identified in this article may be incomplete or inadequate in their ability to explain differential effects of electronic disintermediation on supply chain efficacy. Researchers may also bring theory from other disciplines such as organization science, strategy or communications to bear on the disintermediation issue, perhaps with complementary, alternative or even conflicting conclusions. And investigators may bring discussion pertaining to other technologies such as expert systems, neural networks or knowledge management systems to bear on electronic disintermediation, perhaps offering complementary, substitutable or even superior capabilities. Such theoretical work can serve to augment and enhance discussion and theory pertaining to disintermediation and lead to generation of research hypotheses for empirical testing. Both theoretical and empirical research along these lines can inform information systems practice and stimulate academic discussion and debate. This may contribute to continued knowledge and discovery pertaining to the important topic of supply chain management. The present research hopes to help stimulate, focus and facilitate such contribution.

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Appendix. Overview of intelligent supply chain agents

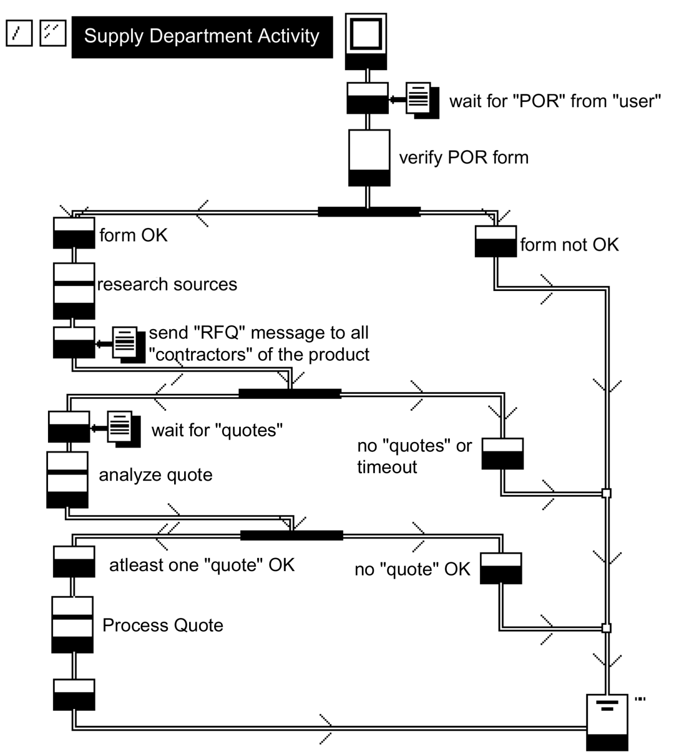
In this Appendix, we draw from Nissen (2000) to discuss an intelligent supply chain agent implementation. We briefly describe the agent-based supply chain process design and then outline the structure and behavior of an agent federation used for integration. This discussion is purposely presented at a managerial level. The interested reader can refer to prior work (especially Mehra and Nissen, 1998; Nissen and Mehra, 1998), on which the Appendix builds, for additional technical details.

Multi-agent system design begins with the enterprise process itself, reflecting an emphasis on the enterprise and organization, as well as agent technology. Of the 16 activities associated with a COTS software supply chain, we initially designate seven of them as particularly promising for performance by intelligent agents. Each of these seven activities is associated with commercial exchanges along the supply chain, and their effective performance requires considerable process-level knowledge by human intermediaries. It is important to note this process design calls for human knowledge workers and machine agents to share responsibilities for process performance.

Our agent-based supply chain implementation involves three agent classes – one each for the user, procurement department and contractor participants along the supply chain. Each of these three supply chain agent classes is specialized through process-level knowledge and designed to be explicitly tailorable to reflect specific rules, priorities and preferences within the context of an individual in the organization. This allows for commonality of design at the agent-federation and class levels along with flexibility in the instantiation and usage of individual agents.

Behaviors for agents in each class are defined using Grafcets and implemented through objects, methods, rules and messages. Grafcets are derived from work on Petri Nets (e.g. Murata, 1989; Peterson, 1981) and have been accepted as an international standard (IEC 848 and IEC 1131-3) for specification of programmable logic controllers (David and Alla, 1992; David, 1995). The Grafcet presented in Figure A1 builds upon the design of Nissen and Mehra (1998) and depicts the behavior of the procurement department intermediary along an enterprise software supply chain. The Grafcet flow begins with the intermediary waiting for some user in the enterprise to convey his or her procurement requirements through a purchase order request (POR) form. When such a POR form is received, the agent first uses its purchasing knowledge to verify the document (e.g. for completeness, conformance to procurement policies and procedures). The Grafcet shows a transition following this first step, which marks a branch in its subsequent behavior depending on the results of its POR verification. Each such transition includes rules to define the conditions required for an

Figure A1 Grafcet for procurement department behavior



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agent to proceed to the next step or set of activities. Steps and transitions are used in this manner to define the agents' behaviors. Grafcets used to define agents representing buyers and sellers are developed in a similar fashion.

Agents from each of the three classes are instantiated and specialized to reflect the knowledge, work environment, tasks and preferences of various principals along the supply chain (e.g. buyers, intermediaries, sellers). The agents communicate with one another using messages (e.g. purchase requests, requests for quotation, quotations, orders, invoices) and coordinate their activities through specialization. For example, the user agent performs only those supply chain tasks delegated to it by the buyer, and likewise for agents representing principals in the procurement department and vendor organizations. The knowledge embedded in agents via Grafcets provides them with a workflow-like "script" of what tasks need to be performed, when each task is ready for performance and how to perform each task. This knowledge and workflow combine to enable agents to effectively, virtually intermediate supply chain activities.

As a note, the proof-of-concept, intelligent agent application outlined in this Appendix has been implemented and used in the supply chain of a major enterprise. Its performance in terms of technical feasibility has been good, but to date it has been authorized only to conduct simulated COTS software transactions. Extension of this multi-agent system to procure products and services beyond COTS software, and assessment of the system making bona fide purchases and sales, represents a high priority study topic for future research.