Prospects for Operations Research in the E-Business Era

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The digital economy is creating abundant opportunities for operations research (OR) applications. Several factions of the profession are beginning to respond aggressively, leading to notable successes in such areas as financial services, electronic markets, network infrastructure, packaged OR-software tools, supply-chain management, and travel-related services. Because OR is well matched to the needs of the digital economy in certain ways and because certain enabling conditions are coming to pass, prospects are good for OR to team with related analytic technologies and join information technology as a vital engine of further development for the digital economy. OR professionals should prepare for a future in which most businesses will be e-businesses.

We may be living through the business equivalent of the Cambrian explosion when, after 3.5 billion years of sluggish evolution, a vast array of life forms suddenly appeared in only 10 million years. New business models and ways of organizing and operating businesses are appearing in comparably rapid profusion, driven by stunning advances in the information technologies.

As managers pursue organizational change on a massive scale, they have focused to the point of preoccupation on the opportunities presented by modern information technology. The need for more decision technology has been growing all the

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while, but only recently have competitive pressures begun to build for more applications.

Fortunately, new data sources, operational business software, intermediaries, and data-exchange standards are emerging that are very conducive to decision technology. Thus the digital economy is entering a phase in which decision technology seems poised to rise and join information technology as a vital engine of further development.

What kinds of opportunities does the dawning e-business era offer OR, and how has OR fared in taking them up? We have inquired widely in academia and in industry over an extended period. We find that, after a slow start perhaps obscured somewhat by secret projects (we encountered more than a dozen), OR practitioners are now beginning to capture some of their abundant opportunities.

Here are some examples, and we shall recount many more in their proper places.

—Hewlett-Packard Company uses real option modeling for dynamic pricing and for managing supply/demand risk as a participant in High-Tech Exchange, a procurement-oriented electronic market for companies in computing and related industries [Billington 2000].

—MarketSwitch uses constrained optimization to make ad- and promotion-placement decisions for Internet advertising networks and e-commerce sites. Its software takes into account the ad-promotion pool, associated advertising and partner contracts, and other constraints, working in real time as customers interact with Web sites. (Underlined phrases correspond to URLs, compiled at the end.)

—OptiBid, an integer-programming-based, multiattribute, Internet-enabled, combinatorial auction system, is used by dozens of large shippers to select transportation providers in an online marketplace.

—Strategic Data Corp. uses segmentation based on hierarchical clustering, a rule-discovery data miner [Cooper and Giuffrida 2000], and a real-time learning engine to personalize Web-site content for its clients.

—Trajecta, Inc. uses predictive and stochastic optimization models to help banks manage their credit-card portfolios, including online applications [Smith 2000].

—United Sugars Corporation uses a Web-based architecture to deploy its production, distribution, and inventory-capacity optimization application [Cohen, Kelly, and Medaglia 2001].

Market forces will likely increase the rate of progress, but we believe OR professionals need to extend their technical repertoire and change some of their ways to approach their full potential in the new era. They need to

—become better informed about application opportunities in the digital economy;

—develop the skills called for by e-business projects, including those relating to information and communication technology, certain emerging OR topics, and the design of e-business processes;

—actively seek out such projects;

—publicize their successes at least through house organs, the trade press, and INFORMS.

OR academics will find ample challenges in supporting the first two items with applicable research and education.

The first item is the main focus of this article. Observations on the second also occur throughout, with more pointed commentary at the end.

In what follows, we sketch a view of the e-business landscape to provide some perspective on a very large territory. Next we identify where OR applications appear most frequently within this landscape. Then we review applications and opportunities in four selected areas: information goods and services, supply-chain management, network infrastructure, and software tools for decision technology. Based on this review, we present what we believe are OR's particular strengths in the context of the digital economy and selectively illustrate these with discussions of customer-relationship management and real-time OR. We conclude by drawing some actionable implications for practitioners.

The E-Business Landscape

Our view of the e-business landscape (Figure 1) serves as a framework for what follows and introduces essential concepts. We necessarily focus on online (mainly TCP/IP-based) rather than offline activity, but these are converging so fast that it will soon be regarded as archaic to speak of one as though separate from the other. TCP/IP (Transmission Control Protocol/Internet Protocol) is the protocol suite on which the Internet is based.

1. Consumer-Oriented Activity

Revenue Directly from Consumers	*187 (2004, B2C part)*
Information goods & services	
Physical goods & services	
Revenue from Advertisers	*27 (2004)*
Non-Revenue	*0*
Affinity groups	
Free services	
Image-building	

2. Business-Oriented Activity

Direct Transactions	
Information goods & services	
Physical goods & services	*3,000 (2004, B2B goods)*
Mediated Transactions	*220 (2003, B2B services)*
Information goods & services	
Physical goods & services	
Intranet Activity	
EDI Activity	*780 (2003)*

3. E-Business Infrastructure

Network Infrastructure	*198 (1999)*
Network Applications	*101 (1999)*
Decision Technology	*24 (2004, software only)*
Software Tools	
Applications	

Figure 1: The e-business landscape has three major parts: the first centers on the needs of end consumers, the second on the needs of businesses, and the third on the infrastructure needed to support the other two. The two-level classifications of the individual parts draw distinctions needed to understand this landscape. Numbers in italics are annual revenue estimates in billions of dollars for the US except as noted. We synthesized the business-to-consumer (B2C) and business-to-business (B2B) estimates from Kafka [2000], Putnam [1999], Sanders [2000], and Williams [1999]. Russell and Keith [2000] provide the advertising estimate; Lawrence [2000] provides the EDI estimate, and Barua and Whinston [2000] provide the network estimates, which are worldwide Internet-related sales of US-based companies (these numbers are growing very rapidly and are not directly comparable to the others since they pertain to four-to-five years earlier). The decision technology estimate is a worldwide lower bound inferred from Morris [2000]; associated services are worth a small additional integer multiple.

The e-business landscape contains two major divisions, (1) consumer-oriented activity and (2) business-oriented activity, both supported by (3) the e-business infrastructure. Consumer-oriented activity comprises business-to-consumer, government-to-consumer, and consumer-to-consumer activity. Business-oriented activity comprises business-to-business, business-to-government, and government-to-business activity. We devote little attention to government activity, although US government-to-consumer and government-to-business activity amounts to some $450 billion annually in fees and fines (and trillions in taxes), and business-to-government sales of materials and services totals about $550 billion across all levels of government [*The Economist* 2000a]. Nor do we consider consumer-to-consumer activity, which thrives via such consumer auction sites as eBay, online classified advertising, and portal sites that facilitate communication among individuals (for example, Web-based e-mail, instant messaging, and Web space for individuals and communities). However, commercial consumer-to-consumer intermediaries and the fees and commissions they collect are part of business-to-consumer activity.

We subdivide consumer-oriented activity according to revenue source: directly from consumers through sales, access charges, subscription charges, commissions, and the like, or from nonconsumers in return for visibility to consumers (including sponsors and those who pay for referrals). Non-revenue-producing online activity can also be relevant to e-business (and to OR [Geoffrion 1998]). For example, affinity-group Web sites (demographic, geographic, or topical) often contain serious discussion of commercial products and services and facilitate access to them.

We subdivide business-oriented activity into that conducted (1) directly between the essential parties, (2) with the help of intermediaries (for example, electronic markets or exchanges), (3) via an Intranet, and (4) via EDI (electronic data interchange). All but the last use Internet technology exclusively. The first two use either the public Internet or *extranets*, which are members-only networks run by individual organizations, often implemented as virtual private networks on the public Internet. *Intranets* use secure, intraorganizational, Internet-technology-based networks typically implemented as private networks or as virtual private networks.

Organizations use intranets for a variety of internal, often operational, purposes—accessing customer records and internal reports, conducting administrative procedures, collaborating, distributing corporate information, providing personnel services, training, and automating work flows [King 2000]. They also use them to conduct internal activity, mainly to transfer goods and services using internal prices (interplant transfer, chargeback for computer services, and so forth).

EDI predates Internet-based e-commerce by about two decades and still surpasses it in magnitude but is growing much more slowly because of its more limited functionality, relative inflexibility, and higher costs. Legacy EDI activity will occur for many years, with some of it migrating to extranets, but most new EDI applications are implemented using Internet technology and XML (extensible markup language).

We distinguish between physical goods, like cars and computers, and (digitizable) information goods, like magazines and music. Similarly, there are physical services, like transportation, and (digital) information services, like news feeds. When completely digitized, information goods and services incur negligible marginal production costs after the first unit, no marginal transportation costs (except when content-delivery networks are used to serve content from caches), and no marginal inventory costs (except for obsolescence costs in some cases). Moreover, they can be reproduced and moved in unlimited quantity almost instantaneously. Physical goods and services do not enjoy these magical qualities. They require supply chains whose annual costs approach $1 trillion in the US [Delaney and Wilson 2000].

Electronic marketplaces could develop into important OR application venues.

For physical business goods and services, we also distinguish between spot and prearranged transactions. The digital economy is greatly increasing the frequency of such spot activity as buying and selling capacity and inventory. As Delaney and Wilson [2000] argue, the stage is set for an epic struggle between such markets and traditional ways of doing business based on persistent relationships.

A huge e-business infrastructure supports all of this activity. The foundation is the network infrastructure, which includes information appliances (networked PCs, personal digital assistants, cell phones, and other devices), servers, access technologies such as cable modem and DSL (digital subscriber line), backbone technologies, fiber optic cable, content delivery networks, networking hardware and software, Internet-access and backbone service providers, network storage providers, and secure commerce infrastructure (for example, digital certificates). Components are sometimes packaged and offered as infrastructure targeted towards specific markets. An important example is the ASP (application service provider) that operates secure server farms in data centers with highly available connections to ISP (Internet service provider) backbones. Such ASPs offer a platform for making software available as a service (Figure 2).

Network applications build on network infrastructure to enable e-business. These include software for Web applications development, search, and transactions and such services as e-business consulting and online training.

Decision technology adds value to network infrastructure and applications by making them smarter. We use *decision technology* inclusively to refer to modeling and solution techniques in the tradition of classical operations research, statistics, and parts of mathematical economics, to symbolic and numeric reasoning techniques from artificial intelligence, and to the implementation of these techniques in software. In our view, OR needs this breadth in the present era. Within decision technology, we distinguish between applications and the software tools that enable

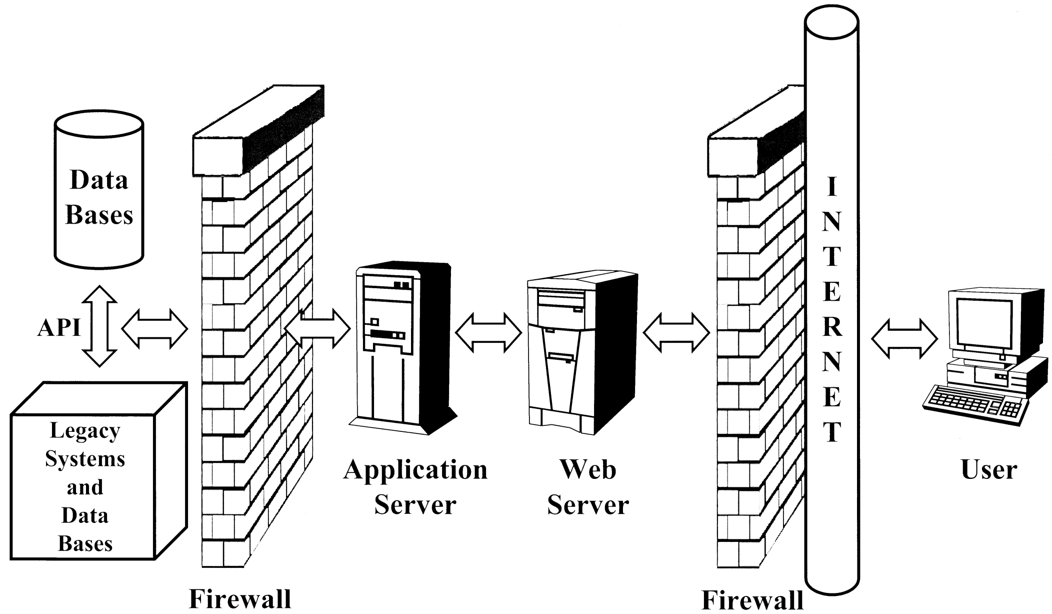

Figure 2: An application service provider (ASP) offers access to application software running on an application server via the Internet and a local client program (often a Web browser). The application server has secure access to applications and databases, legacy or otherwise, through application program interfaces (APIs). This is an increasingly popular way for software vendors to make their software available as a service.

them. For example, a Web-ready component library for optimization would be a *tool*, whereas software for online investment portfolio optimization that uses this component library would be an *application*.

In our extensive search for applied work on the intersection of OR and e-business, we found the most activity in four areas of the e-business landscape (Figure 1):
—within business-to-consumer and business-to-business commerce in information goods and services, applications in online financial services and travel-related services;
—within business-to-consumer and business-to-business commerce in physical goods and services, applications in supply-chain management and electronic markets;
—within network infrastructure and applications, applications in network design and quality-of-service improvement; and
—within decision technology software tools, the packaged software component.

The remainder of the landscape may have received less attention to date from OR practitioners, but do not discount its future potential. For example, advertising and customer relationship management applications are heating up rapidly. The decision technology applications category is a special case since every such application is associated also with some other portion of the landscape.

We now review in some detail the four areas of the e-business landscape, with particular attention to opportunities.

Information Goods and Services

Information goods include books, greeting cards, music, software, video games, and videotapes. Although these goods are traditionally manufactured and delivered in physical form, they can be digitized and so need not be materialized for customers who have the means to receive them digitally—a solid state player to display books, a screen to display an electronic greeting card, and so forth. Over time, digitizable goods will increasingly be delivered to customers in digitized form—almost completely bypassing, for downloaded goods, physical manufacture and all that comes afterward [Johnson 2000]. Supply chains for information goods in physical form are therefore doomed to become less important.

The main categories of *information services* are entertainment, financial, news, telecommunications, and travel, but only to the extent that their delivery and business processes are digital. The ASP industry, expected to explode as software becomes more of a service and less of a product [Apfel 2000], cuts across most categories. Since administrative, personal, and professional services usually require people for performance, we categorize them as physical services (an exception is the Web-based SmartSettle negotiation-support system, which uses mixed integer programming at its core and does not require a professional facilitator). In travel, we classify an airline's direct-sales Web site under physical services, since fulfillment requires flying airplanes, and agents under information services, since they deal only in tokens for services that others will fulfill.

Based on detailed forecasts by Forrester Research, we estimate that information goods and services, exclusive of EDI, will account for roughly one-third of the $187 billion business-to-consumer activity projected for 2004, a much smaller fraction of the $3 trillion business-to-business goods projected for 2004, and roughly half of the $220 billion business-to-business services projected for 2003 (Figure 1).

One can distinguish two kinds of managerial opportunities for OR in connection with information goods and services: to help design and operate e-business processes and to analyze business issues of a less recurrent nature.

The processes are of course very different from those for physical goods and services, although many analogies can be drawn: information goods and services have to be created, put in saleable condition, made available for sale, and delivered to customers. Content-delivery networks and Web caching [Chan et al. 1999] are important parts of such digital supply chains.

Economists have had the most to say about business issues. A good example is the book *Information Rules*, in which Shapiro and Varian [1998] cover pricing, product versioning and bundling, intellectual-property-rights management, lock-in, network externalities, and other issues for information goods and services. They argue that the digital economy is not as novel as often portrayed and that well-established economic ideas can be applied to craft strategy and deal with common e-business issues. They include no explicit mathematics or models, but it is obvious that models could be formulated using standard ideas from economics, especially from microeconomics (see the simple mathematical models on the Information Rules Web site under "Teaching").

This book and other economics-based works on the digital economy [Bakos 1998; Bossaerts, Fine, and Ledyard 2000; Smith, Bailey, and Brynjolfsson 2000; Vakrat and Seidmann 2000] contain an implied challenge to OR professionals: to attempt modeling applications that carry economic analysis of e-business issues in the direction of more detailed, quantitative studies of particular problems faced by particular companies.

Moving from stylized economic models to real applications in the OR tradition

OR professionals need to extend their technical repertoire.

will require less reliance on convenient assumptions, more reliance on computational rather than analytical solutions, and sometimes facility with such tools as Mathematica that support symbolic as well as numeric reasoning. Achieving such a fusion of the two traditions is a major challenge facing OR, and success would also strengthen the strategic capabilities of OR practice, something not always seen as a hallmark of the field.

OR can also add value to information goods and services by direct incorporation. For example, a book or technical manual downloaded to a portable display unit containing a processor could include some content computed on demand from stored data and models. Tables and graphs, for instance, need not be static but could be computed as needed by a reader who revises the default parameter settings of an underlying model. In this way, OR can become part of books, manuals, and briefer works in any of its many application domains. (One enabling technology toward this end is MathML, a markup language for mathematical processing.)

Packaged software provides a more familiar context for OR to add value. For example, incorporating OR into geographic information system (GIS) software can yield large practical benefits [Weigel and Cao 1999]. Leading GIS software vendors, such as ESRI, now offer Internet map servers and OR components that can serve as platforms for OR applications. For instance, with real-time data about truck locations and traffic, GIS and OR already help retailers achieve greater efficiencies in product delivery [Brown 2000; Partyka and Hall 2000].

Spatial data modeling, which is greatly facilitated by GIS, will play an important role in mobile commerce (commerce enabled by mobile information appliances, such as Internet-enabled cell phones and wireless personal digital assistants, whose numbers are forecast to grow five-fold from 1999 to 2003 [Meeker and Mahaney 2000]). The next generation of these appliances will be location-aware based on the Global Positioning System or ground-based networks or a combination of both. Given knowledge of the location of users carrying these appliances, a range of information services that exploit the availability of spatial maps and OR algorithms are possible. Two examples are real-time routing to avoid congested roads and geographically specific recommendation systems that consider interests and preferences when suggesting restaurants or other stationary facilities.

"OR Inside" is still in the future for most information goods and services, but it is very much in the present for some Internet-based services.

Financial services. OR methods have long played an important role in financial applications [Jarrow, Maksimovic, and Ziemba 1995; Luenberger 1998]. Examples of practical successes include the analysis done by the Management Science Group at Merrill Lynch Private Client Group on a strategic service-pricing response to the discount online broker challenge [Nigam, Labe, and Altschuler 2000]; products from Web-savvy, OR-based companies, such as Algorithmics (enterprise-wide financial-risk-management software for market, credit, liquidity and operational risks) and BARRA, Inc. (portfolio analytics and enterprise-risk management); and high-impact work in asset and liability management at Towers Perrin-Tillinghast [Mulvey, Gould, and Morgan 2000] and in portfolio construction at GMO [Bertsimas, Darnell, and Soucy 1999].

Inevitably, OR-based financial products and services are finding their way online. Online business financial services is the largest of the business-services sectors, forecast to expand from $7.3 billion in 1999 to $80 billion in 2003 [Putnam 1999]. One such service is the Bond Connect online marketplace for fixed-income securities, which uses integer programming to help match and price trades in a combinatorial auction setting. The novel design, based on work by Bossaerts, Fine, and Ledyard [2000], promotes liquidity by permitting contingent cross-market orders that reflect whole-portfolio considerations. Originally available only over a proprietary network, it is now available over the Web. Another service is investment-portfolio risk management, in which recent advances based on scenario simulation enable ASPs (for example, Credit Suisse First Boston) to perform all the heavy model computations while their institutional clients perform the light, portfolio-specific risk calculations with proprietary data [Dembo et al. 2000; Young 2000]. This partitioning of work enables one to take advantage of ASP functionality while still preserving client confidentiality. A similar service is available to individual investors.

Sadly, many firms found no P in ERP.

Among consumer services, automated online financial advice is forecast to explode in penetration from an estimated 1.8 million US households at the end of 2000 to 20 million by 2005 [Punishill 2000].

Online advisory financial services increasingly embed optimization routines. An early example is Optimal Retirement Planner from Sundown Software Systems, offered free through an ASP. It relies on linear programming instead of on simple formulas and rules as traditional retirement planning calculators do. Based on current savings, planned contributions, and desired estate, it formulates a model and computes a schedule of transfers and disbursements from retirement accounts to maximize the amount of annual after-tax money available for spending through the term of retirement.

A better-known ASP service for optimization-based investment advice is Financial Engines Investment Advisor, which advises on most tax-deferred retirement accounts. It offers basic features for free and more advanced ones for a fee. It uses quadratic programming for portfolio optimization and Monte Carlo simulation to forecast probable investment outcomes. Several other firms, including BARRA, Inc., offer portfolio-optimization services, financial-risk management, and investment analytics via the Web.

OR is also finding its way online in lending and in the analysis of electronic markets. ILOG, Inc. has developed a real-time constraint-programming application [Lustig and Puget 1999] to online lending, First Union Loan Arranger, for First Union Home Equity Bank. It takes the customer's preferences into account and to calculate the best loan for the customer subject to constraints imposed by the bank's loan-approval policies.

Clemons and Weber [1997] applied information economics and computer simulation to obtain strategically valuable insights into screen-based securities markets, and probably also into emerging electronic markets in which highly profitable accounts have traditionally subsidized unprofitable ones (for example, some financial services, insurance, and telecommunications markets). The problem, they say (p. 1696), is that ". . . cross-subsidization attracts new entrants with targeted marketing strategies, based upon opportunistic cream skimming. . . ." The Internet is famous for facilitating this sort of market efficiency.

Other opportunities to embed OR surely will follow from the success of online trading and investing [*Wall Street Journal* 2000], from the trend toward online banking, and eventually from online insurance [*The Economist* 2000b].

Travel-related services. Leisure travel (mainly airline tickets, lodging, and rental cars) is forecast to be about 12 percent of all business-to-consumer e-commerce in 2004 [Williams 1999], a share considerably larger even than the total of computer hardware and consumer electronics. Business travel is forecast to be about 17 percent of all online business services in 2003 [Putnam 1999], which is about half of business financial services. Moreover, business travel is forecast to have by far the largest penetration rate among the major groups of business-to-business e-commerce services: about 32 percent of total business travel (online or offline). Our focus here is on the information services related to travel, not the physical services.

The airline industry pioneered e-commerce about four decades prior to the advent of the Web, deploying some of the world's first business-to-business systems. Thus, OR practitioners can look to the airlines for experience, technology, and applications that may be adaptable to other e-business domains. The discussion by Smith et al. [2001] of Sabre's use of OR in the airline industry is instructive even beyond travel-related information services:

(1) The Sabre computer reservation system was "the first real-time business application of computer technology." This system and its competitors formed the basis for today's global distribution systems for reservations, which support multiple dis-

tribution channels and vendors in many travel-related industries. They are similar in function to, and predated by more than 20 years, the vertical Web portals currently the focus of frenzied activity in many industries.

(2) Sabre's low-fare search engines have been used by travel agents since the mid-80s. The enormous user-base expansion that followed public access to them via the Web increased both the number and the kinds of database queries to be processed, forcing a substantial redevelopment effort to deal with the associated optimization problems. Sabre's experience offers scalability lessons for other OR applications that must migrate to the Web and possibly also for Web *shopbots*—programs that consumers use to search the Internet for goods and services meeting low-price and other criteria.

(3) The display-ordering problem is fundamentally important to dynamic Web page design, especially for the results of shopbots, recommendation systems, and search engines. The essence of this problem is how to order the results to promote some objective—such as to favor some product or vendor or to direct traffic to some Web site—to the maximum extent permissible under regulatory, ethical, and market constraints. This can be formulated as an optimization problem if one can model how display order influences viewer preferences. Sabre's success with such applications should encourage others to tackle similar opportunities in other e-business contexts.

E-prefixes will become passé as online and offline economies fuse.

(4) Yield management, originally a blockbuster airline application, is diffusing rapidly throughout the hospitality and transportation industries and beyond (including business-to-business) as e-mail and the Web speed up communication with customers. These technologies allow companies to change prices—customized to individuals or groups—globally and instantly as commitment deadlines approach. They also enable rapid customer responses to price changes and subsequent real-time or near-real-time negotiations.

Online leaders are integrating yield- and revenue-management systems with core business processes in such areas as last-minute travel deals, natural gas trading, and ticket sales. For example, OptiYield-RT is a real-time yield-management system for truckload carriers based on load data from the carrier's order-entry system, demand data from a cooperating Internet-based exchange, current truck locations according to global-positioning technology, and other data. Another yield-management product, NeoYield from NeoModal.com, is designed for ocean carriers to use on an ASP basis. It uses demand information from carrier forecasts, network-capacity data (vessel space, container availability, and terminal births), and carrier-cost data to decide what demand to satisfy at what price and how best to reposition empty containers [Hingorani 2000].

In addition to the well-developed solution techniques for perishable products and services pioneered by such airlinebred specialists as PROS Revenue Management, Inc., Sabre Inc., and Talus Solutions (now part of Manugistics, Inc.), there are techniques for other formulations of the dynamic-pricing problem [Andrews 1999; Kephart, Hanson, and Greenwald 2000]. Dynamic pricing will play a crucial role in many online markets, including online auctions [Lucking-Riley 2000], and OR technology is very useful for designing associated business processes. For example, Home Depot uses integer programming in an Internet-based combinatorial bidding application for contracting transportation-carrier capacity [Keskinocak and Tayur 2001].

Supply-Chain Management

Physical goods and services make up the lion's share of the e-commerce forecast for 2004: roughly two thirds of the projected $187 billion business-to-consumer activity and a much larger fraction of the projected $3 trillion business-to-business activity (Figure 1). If supply-chain costs (inventory, transportation, warehousing, and logistics administration) consume anywhere near the same proportion of the online share of the gross domestic product as they do of the offline share, about 10 percent [Delaney and Wilson 2000], supply chains will play a crucial role in the digital economy.

OR-powered supply-chain management will be important in the online economy, as it has been in the offline economy, for strategy, tactics, and operations. The digital economy provides further reasons to use OR, including these:

(1) Enterprise resource planning (ERP) and advanced planning and scheduling (APS) vendors are striving to become Internet centric and to meet brisk demand for better planning and scheduling capabilities within a context that is rapidly expanding to include e-business.

(2) Business-to-business electronic markets are growing rapidly, with spot markets flourishing and dynamic pricing becoming pandemic.

(3) The Internet is stimulating much more supply-chain coordination and collaboration with suppliers and customers.

(4) The Internet is stimulating expansion of supply chains to include product-design and customer-relationship management.

(5) The trend toward mobile communications and computing in the trucking industry is accelerating Internet-based decision-support applications in trucking.

(6) The Web greatly facilitates deploying highly interactive applications.

These are some of the ways in which the digital economy adds to the importance, opportunity, or effectiveness of OR-driven supply-chain management. They warrant elaboration.

(1) ERP systems have been implemented by roughly half of all large companies in the US and Europe, are spreading rapidly to midsize firms, and are incorporating e-business functionality. Nearly $10 billion is spent annually on ERP software licenses in the US, and still more on implementation and associated services. Sadly, many firms found essentially no P in ERP. These systems focused on transactions, with little provision for planning and scheduling. Worse, they often obliterated valuable OR applications.

A brisk demand for supplemental APS software developed. Optimization became a panacea to such an extent that the word is now debased to mean merely "try to improve." Although everyone wants "optimal" plans and schedules, most planning and scheduling software from APS and ERP vendors produces solutions that are workable but often far from optimal. Optimality or something close to it looks like a long-term objective, and that is an enduring opportunity for OR. ERP vendors (most now with APS capability) have been scrambling to incorporate better planning and scheduling into their products, as well as Internet-enabled connectivity (for example, with EDI and XML-based document-exchange standards) and greater interoperability with third-party software [Sodhi 2001; Sprott 2000].

An important legacy of the ERP movement is that it made available far more high-quality transactional data for modeling purposes. OR practitioners can tap this data, but connecting model-based applications to ERP systems requires using contemporary, widely adopted application-program interfaces [Sprott 2000]. This can be done. OptiFlow, for example, interfaces with ERP, APS, and transportation-management systems; it optimizes routing and load consolidation for trucking companies each night, using the Web to obtain data and to distribute solutions.

(2) Electronic markets are forecast to account for about half of business-to-business e-commerce trade in 2004 [Kafka 2000]. Online markets (these exclude bilateral trade between pairs of trading partners) often take the form of auctions and exchanges hosted by buyers, sellers, or intermediaries [Bakos 1998; Kaplan and Sawhney 2000; Lucking-Riley 2000]. They support prearranged and spot buying and selling. In spot trading, there is a strong trend toward transaction prices that change in response to the latest information about vendors (for example, capacity, demand, inventory, and scheduling) and about buyers (for example, bidding behavior or "clickstream" history). (A *clickstream* is a navigational path.) This creates opportunities for analysis and for model-based systems to set prices, bids, and negotiating positions rationally. Keskinocak and Tayur [2001] explain some of these opportunities in a way that recognizes the roles of both economics and OR.

Economic theory is having a major practical impact on online market design; for examples, see Market Design Inc. (auction market design) and Perfect.com (RFQ process automation for exchanges). Economics becomes stronger yet when more OR technology is added, as in the following examples:

—Beam, Segev, and Shanthikumar [1999] use Markov chains and optimization to design multi-unit auctions taking into account lot sizing and pricing.

—Ishikida et al. [2000] use integer programming for deciding which offers to accept in their design for a combined-value call market (a kind of combinatorial auction) for trading air-emission permits. This design formed the basis for California's Automated Credit Exchange, which has been operating successfully since 1995 as the world's first Internet-based business-to-business exchange. Subsequently, similar technology has been used to build other online, combined-value call markets (Net Exchange).

—Vakrat, Pinker, and Seidmann [2000] use dynamic programming and Bayesian learning to obtain methods for designing optimal multiperiod, multiunit auctions.

—Vakrat and Seidmann [2000] present an empirical study of real business-to-consumer auction data, which they use to motivate an economic analysis aimed at providing a theoretical basis for their observations and guidance for auction design.

There are indications of an important trend among electronic market makers: that many will provide OR functionality to participating firms because this can add substantial value. Such functionality could include optimal auction design and bidding services, individual and collaborative supply-chain management, dynamic pricing services, and MCDM (multicriterion decision-making) aids for procurement. Electronic marketplaces already offering OR functionality include Digital Transportation Marketplace from Logistics.com, FreightWise and eConnections (built with Manugistics, Inc.'s ExchangeWORKS electronic exchange platform), mysap.com, and marketplaces built using the i2 TradeMatrix suite of components. Furthermore, since some OR applications are better run by an ASP than by the company they serve [Sodhi 2001], electronic marketplaces may pick up additional applications of this sort.

If OR functionality becomes widespread, electronic marketplaces could develop into one of the most important of all OR application venues. At a minimum, we expect them to become an important new source of market data and industry statistics with which knowledgeable participating firms can build their own models.

(3) Internet connectivity is causing supply-chain management to expand in the direction of suppliers and customers, thereby causing the physical scope of supply-chain models to expand [Sodhi 2001]. For example, the Internet makes vendor-managed inventory more practical, thereby inviting extension of inventory models and software. For another example, the availability of data about capacity, inventory, and demand from trading partners' ERP systems in business-to-business marketplaces sets the stage for integer programming to perform multiway matching of supply and demand for manufacturing capacity and inventory [Keskinocak and Tayur 2001].

(4) The Internet also facilitates expanding supply-chain management in the direction of product design, sales, and customer-relationship management (CRM) [Sodhi 2001]. Again supply-chain models must be expanded, this time with respect to their functional scope.

Keskinocak and Tayur [2001] and Sodhi [2001] elaborate further on these four points and cite companies that are exploiting these OR opportunities.

(5) Fuel is a major operating cost in the half-trillion-dollar trucking industry, making fuel-purchase optimization important. ProMiles Online was the first to offer this service online, with an ASP application that makes the daily updating of fuel prices transparent to users. Another ASP service, OptiStop, combines this application with optimal routing. It uses the Web to reach a carrier's system, which in turn reaches the mobile satellite communication terminal that many trucks carry; alternatively, owner-operators can use OptiStop directly via a Web-based interface.

Such OR applications are likely to come into general use. Computers are already common in truck cabs (about 20 percent in 2000), truck stops are increasingly computer friendly, and most trucks should soon have mobile Internet connections and location-finding equipment. The latter enables new rendezvous tactics for swapping trailers or parts of loads away from fixed distribution facilities, which poses new modeling challenges.

(6) The Web makes it inexpensive for the first time to deliver highly interactive OR applications at the point of need on a global scale. For example, it is now practical to make MCDM methods available with the interactivity needed for such applications as procurement. Frictionless Commerce offers software that incorporates such methods tailored to business-to-business purchasing for maintenance, repair, and operating supplies. Several companies offer such methods for business-to-consumer applications, including financial services. For another example, an LP-based, ASP-hosted contract negotiation tool like NeoSelect from NeoModal.com would be impractical to deploy other than online because of the negotiations and many cost-service trade-off scenarios needing solution during a typical global ocean shipper's contracting period, which may involve hundreds of prospective trading partners [Hingorani 2000].

Network Infrastructure

The meteoric growth of the Internet is well documented [Zakon 2000], comprising more than 93 million hosts in over 200 countries as of July 2000. E-business applications are both leveraging and further driving the growth of this infrastructure. As these applications mature, people are paying increasing attention to quality-of-service issues. According to a Forrester Research analyst, "Eight seconds isn't fast enough any more when it comes to downloading Web pages. . .expectations are around four seconds, no matter what kind of connection you're on" [Nelson 2000]. Improving response time requires attention to resource allocation and pricing, which OR technologies are well positioned to address.

From the consumer's quality of service viewpoint, the network infrastructure for e-business has three major components:

(1) Local consumer access to the Internet (the so-called last mile), which is migrating from narrow-band, dial-up access to high-speed broadband access using either DSL or cable modem technology;

(2) The Internet and networks that use Internet technology, especially intranets and extranets, which deliver the content from a server to the user's browser; and

(3) The Web-server farms and transaction-processing systems that facilitate access to content.

The delays users encounter may be caused by problems with any of these components.

Local access networks. Even with the growing adoption of broadband technologies, dial-up access to the Internet over the public-telephone network will remain the dominant mode until about 2005 [Meeker and Mahaney 2000]. Calls to ISPs differ from voice calls in their statistical characteristics. Their greater length has resulted in an increase in blocked calls, both voice and data. In redesigning their networks to handle these fundamentally different types of calls, local exchange carriers are using queueing theory and new statistical models of calling patterns that differ from the Poisson models traditionally used to design voice networks [Willinger and Paxson 1998].

Researchers have also examined the design and economics of local access to data networks, including broadband Internet access. Fryxell, Sirbu, and Wanichkorn [1999] discuss the economics of TCP/IP-based local-access networks, and Klincewicz [1998] reviews OR methods for designing tributary networks. The application of OR to these problems requires a strong background in communications networks and technology. Oppenheimer [1999] provides a good introduction to network design, and Cahn and Chan [1998] cover OR approaches to wide-area-network design.

Content delivery networks. Quality of service for content-delivery networks has been studied from three perspectives.

The first is that of Web caching [Rodriguez, Biersack, and Ross 2000]. A *Web cache* is a computer system in a network that monitors requests from clients to servers and stores copies of requested content. When it sees a request for a Web page that has been stored, it serves its local copy. In this manner, caches reduce response time for accessing Web content. Serving from cache also conserves bandwidth that otherwise would be used to retrieve content from originating servers, a plus because the cost of storage is lower than the cost of Internet bandwidth [Christy 2000]. Further, caching reduces the workload of originating servers.

Content-delivery network companies, such as Akamai and Digital Island, own caches, which are located at large ISP access centers. Content-delivery networks must formulate caching policies. These policies are governed by contracts with content providers, who specify the number or placement of their mirror sites, or by objectives based on response time or bandwidth usage [Chuang and Sirbu 2000]. Typically, the policies seek to minimize response time and conserve Internet bandwidth. Given replicated content in the caches, content-delivery networks need to direct incoming requests for content to the most appropriate caches. They want to do this distributed load balancing well because they bill content providers for bytes served. Akamai, in particular, makes extensive use of OR methods such as min-cost multicommodity flow algorithms for this purpose (see Akamai patent US06108703 for global system hosting).

The second perspective related to content delivery is the use of pricing for allocating resources. Currently, Internet pricing is the same for delay-sensitive packets (such as telephony) and delay-insensitive packets (such as e-mail), even though different applications require different service qualities.

In general, analysts have focused on congestion pricing versus pricing at marginal cost of bandwidth. Congestion pricing reflects the delay the allocation of bandwidth to one application causes to other applications. Some analysts use economic modeling [Gupta, Stahl, and Whinston 1999]. Others use statistical modeling to assess the demand for bandwidth and consumers' willingness to pay for different levels of service [Varian 2000]. This may prepare the way for applying yield management to ISP services. Finally, Chuang and Sirbu [1998] discuss the pricing of multicast (many recipients) versus unicast Internet traffic. Pricing has become even more important with the rollout of Internet Protocol Version 6, which permits tagging packets with quality-of-service labels. While backbone ISPs do not currently reconcile accounts for packets exchanged with other ISPs at network access points, pricing issues will likely become more important in the future.

The third perspective on content-delivery networks concerns their design, long a fertile application area for OR [Cahn and Chan 1998]. Jim Crowe, CEO of Level 3 Communications, which has built a coast-to-coast, fiber-based, Internet protocol network, says: "Level 3, at its heart, is a technology-based company and, frankly, the central technology is operations research and optimization, which I tend to think is going to revolutionize all of business over the next 20 years" [Horner 2000, p. 40]. Among other applications, Level 3 uses OR to decide how many empty fiber-optic conduits to put in the ground to minimize expected long-run network costs in light of cost and capability estimates for future generations of fiber. This is an important problem, since optical technology is improving rapidly and trenches are expensive.

The closely related topic of survivable network design has become increasingly important to ISPs. The aim is to maintain network services and minimize congestion after physical or software attacks destroy links or switches [Medhi and Tipper 2000].

Optimizing quality of service on servers. The control and optimization of performance measures for high-volume Web sites requires a fundamental understanding of user-request patterns and their impact. One successful methodological contribution toward this end used stochastic processes and statistics to characterize request patterns for heavily accessed Web servers and tested the results on data from the 1998 Nagano Olympic Games server [Iyengar, Squillante, and Zhang 1999]. IBM now includes these techniques in its leading application-server product, WebSphere, to improve peak-period response times.

To solve network-infrastructure problems, OR practitioners need a good understanding of network protocols (TCP/IP), particularly such application-layer protocols as HTTP, and such concepts as caching. Good starting points are Kurose and Ross [2000] on TCP/IP and Zhang [2000] on the technology underlying packet-switching networks and Internet protocols.

Software Tools for Decision Technology

We focus on packaged, rather than custom-built, software tools for decision technology that contribute toward improving the infrastructure of e-business by facilitating OR work in that context (Figure 1, third division). Whether or not such software is sold over the Web is not our concern here (such sales would register under the second division of Figure 1), nor are the very considerable employment opportunities for OR expertise associated with its design and implementation.

Such software most enhances OR professionals' productivity and the range of products and services they can provide when it has the convenience of Web-accessibility and when it can operate in conjunction with other software in an Internet environment [Bhargava and Krishnan 1998] and hence be incorporated into e-business software. This is perhaps especially true for the "lone" practitioner.

Two types of software are particularly useful to OR practitioners: (1) free software suitable for internal purposes short of incorporation into production-quality application software and (2) commercial software suitable for building Web-enabled, production-quality application software or for doing OR analysis—especially when it complies with e-business application integration standards. Between these two is open-source software, which has considerable potential. It is free, can be included in applications subject to licensing restrictions, and can be of very high quality. Yahoo! reportedly runs largely on such software. Open-source decision-technology software is just starting to appear; for example, IBM's Common Optimization INterface.

Much useful software is now freely available on the Web (sometimes with restrictions against commercial use). For example, with just a Web browser and an Internet connection, anyone can undertake to

—solve many varieties of optimization models using optimization servers and other resources detailed by Fourer and Goux [2001];

—do many kinds of statistical computations using tools available through such sources as StatLib, StatPages.net, StatPoint Internet Statistical Computing Center, and SticiGui;

—produce US and multicountry macroeconometric forecasts using Fairmodel; and

—use Web-enabled, education-grade software, such as WebGPSS (a Java-applet for discrete event simulation), and the Web-based software that is starting to accompany textbooks (for example, the Harvesting Customer Value site has seven marketing-oriented packages), and Java, server, and online offerings, such as those listed in Michael Trick's software compilation.

Over time, application service providers will be making more and more OR tools available via the Web, usually for a fee.

For projects that require building Web-enabled, production-quality application software or that could profit from making models or results accessible via the Web or that need industrial-strength tools, OR practitioners have an expanding array of options:

—DRA Systems offers OR-Objects, a freeware collection of 500 Java classes intended for OR-application development.

—ILOG software components are available for constraint programming, mathematical programming, business rules, and visualization and can be embedded in client-side and server-side Web applications.

—InfoHarvest, Inc. offers a Web hosting service that puts models built with their flagship MCDM product online for secure data gathering, preference surveying, and results/analysis sharing.

—InterNetivity Inc. offers the easily incorporated analysis and reporting engine databeacon, which works in conjunction with HTML data tables to enable interactive graphing, drill-down, sorting, pivot-

ing, and more.
—John Galt Solutions, Inc. offers the ForecastX Engine as an ActiveX control to add forecasting and statistical analysis to Web-enabled applications.
—Lumina Decision Systems, Inc. offers the Analytica Decision Engine (decision analysis, influence diagrams, Monte Carlo, statistics) for incorporation into the back end of custom Web-based applications.
—Meta Software Corporation offers MetaSoft Web for publishing WorkFlow Modeler business process models on the Web or an intranet.
—SAS Institute offers Web-enabled products for data analysis and mining, econometrics, forecasting, OR (decision analysis, discrete-event simulation, optimization, and project management), and statistics. SAS's multitier application-server architecture enables applications to be Web-enabled easily, including dynamically generated HTML pages to communicate results [Cohen, Kelly, and Medaglia 2001].
—SIMUL8 Corporation offers a free player for viewing animated results produced by its simulation package and stored on a Web server.
—StatPoint, LLC offers StatBeans, statistical components in Java for adding statistical content to applications or HTML documents.
—ThreadTec, Inc. offers the Java-based simulation language Silk for developing Web-accessible, discrete-event simulation models.
—TreeAge Software, Inc. offers DATA Interactive, an ActiveX component, for distributing interactive models built with DATA 3.5 (decision trees, Markov analysis, Monte Carlo) over an intranet or the Internet.
—Vanguard Software Corporation offers DecisionPro 3.0, a Web-enabled and e-mail-enabled OR-modeling package supporting decision trees, forecasting, influence-diagram calculations, linear and nonlinear programming, and Monte Carlo simulation. It also offers DecisionScript, built around DecisionPro 3.0 using server-side JavaScript, for building analytic applications with expert-system features.
—WhiteLight Systems, Inc. offers the WhiteLight Analytic Application Server and its component-oriented, drag-and-drop development environment for building Web-based, spreadsheet-like analytic applications.
Other vendors choose to specialize in turnkey installations, such as ALT-C Systems Inc. (which offers TimeTrends e-Forecasting). Still others function as partners, such as,
—AlphaBlox Corporation Inc., which offers a Web-based platform and many components for the rapid assembly and centralized administration of analytic applications [Morris and Garone 1999];
—ExpertCommerce, Inc., which offers the Expert Choice analytic hierarchy process implemented as a Web-enabled business-to-business purchase-evaluation engine; and
—Manugistics, Inc., which offers a suite of optimization engines targeted at supply-chain management and at pricing and revenue management, all of which can be embedded into its ExchangeWORKS platform for building custom public or private electronic trading environments.

Most analytical software companies will

likely have to Web-enable their products [Bhargava and Krishnan 1998] to remain competitive. The bar will have been raised within a few years, and thereafter Web-enablement will be viewed as a competitive necessity rather than competitive advantage.

With the software categories just reviewed changing so rapidly, OR professionals will need to invest extra time staying abreast of such software and compatible implementation architectures.

Why the Digital Economy Needs OR

Some of the kinds of value that OR can add are particularly well matched to the digital economy's needs. Here are six notable strengths of OR whose importance springs from attributes of the digital economy. They are not the ones most commonly mentioned in the context of the off-line economy; OR is far more than merely a way to squeeze costs by another five percent.

(1) OR excels at squeezing value out of data, which the digital economy is creating in unprecedented abundance: auction logs, customer profiles, mobile scanner data, point-of-sale data, process data gushing into data warehouses, transactional ERP data, Web logs, and more. By coupling statistics, data analysis, and data mining [Goebel and Gruenwald 1999; Two Crows Corporation 1999] with decision technology, organizations can turn the data deluge into actionable knowledge.

(2) OR can cope with complexity in design, planning, and operations because it is inherently analytical. *Analysis* means breaking up a complex whole into its component parts; just what is needed to deal with the increasing complexity brought about by e-business.

(3) OR can manage risk and deal with uncertainty using statistics, decision analysis, and probabilistic modeling. In an age when business and technological change is so rapid that the past is a poor guide to the present, let alone the future, it is prudent to invoke model-based approaches to decision making that quantify uncertainty and risk explicitly.

(4) OR's model-building approach is one of the most reliable ways to achieve a deep understanding of business processes and issues. It can be argued that no phenomenon, even man-made ones like business processes, is truly understood until it can be measured and modeled. Hence OR accords well with the premium that management increasingly places on intellectual capital and methods for knowledge discovery.

(5) OR can perform virtual experiments (analyses, simulations) without risking damage to a company's assets or financial performance. With intuition-busting novelty the order of the day, businesses need to avoid failures whose consequences may be exhibited and multiplied by the Web's global reach.

(6) OR can provide decision technology for operational software to handle entire classes of decisions quickly (perhaps in real time, as in many Web applications), repeatedly, and automatically. Even decisions that have long defied automation, such as approving home-equity loans, are now made automatically using decision technology. Information technology is seldom sufficient for automating business decisions, for rules of thumb that work well even 99 percent of the time can generate

huge economic penalties and dissatisfaction when used on a high-traffic Web site. The solution is to wed decision and information technology.

Other conspicuous strengths of OR, such as powerful ways to analyze decisions of great consequence, to achieve true cost minimization in many cases (not just cost reduction), and to make trade-offs, seem not to be especially advantaged by the advent of the digital economy but remain as useful as ever.

Every strength has already been illustrated by cited applications (Table 1). We elaborate further on the first and last.

Exploiting the digital data bonanza. Customer-relationship management is one of the greatest beneficiaries of the IT-induced bonanza of data, and OR is taking advantage of it. *Software Magazine* found CRM to be the fastest-growing sector of the software industry during 1999, and International Data Corporation (IDC) forecasts CRM to be the fastest-growing sector of the packaged analytic-applications-software market through 2004, jumping from worldwide revenues of $486 million in 2000 to $2,374 million in 2004 [Morris 2000]. The aim of CRM is to identify, acquire, serve, extract value from, and retain profitable customers by interacting with them effectively in an integrated way across the full range of customer-contact points for marketing, sales, and service—e-mail, in person, mail, phone, Web, and so on.

Doing this requires making sense of mountains of pertinent data from operational systems (order entry, finance, and shipping), customer-contact records (including call-center servers, reply cards, and Web servers), and third-party sources (for example, credit histories and demographics). This is best done through data mining, statistical studies, and models that ideally maximize lifetime customer value [Chatham 2000]. Some examples of OR in support of CRM follow:

(1) HNC Software Inc. uses neural-network and other predictive technologies to recompute the predicted profitability of individual customers as transactions occur, to better inform efforts to maximize customer lifetime value by balancing credit risk, revenue potential, and customer attrition in financial services, telecommunications services, and other applications.

(2) Market Switch Workstation is an enterprise-level decision-support application that uses constrained optimization for real-time, multioffer optimization for inbound marketing (call center, Web) and customer care. From a portfolio of options, the software determines what marketing promotion, advertisement, or customer-service response will maximize the financial return of that customer. It also does multioffer, enterprise-wide optimization for outbound marketing (direct mail, e-mail, telemarketing) to find the most profitable offers to release. This product is incorporated into the products of marketing-automation-service providers, such as Prime@Vantage Optimizer and Xchange Dialogue.

(3) Trajecta, Inc.'s Optimization Simulation Environment uses neural networks, regression, and single-stage stochastic linear programming to predictively model key customer behaviors and maximize (with robust optimization methods) the

These strengths of OR. . .	. . .Help meet these challenges of the digital economy	Illustrative applications (discussed in the text)
Exploiting the data bonanza	Digitally formatted data now dominate nondigital data by more than an order of magnitude and are increasing far faster [Lyman and Varian 2000].	Customer-relationship management (see the subsection "Exploiting the digital data bonanza"); Electronic market services (Digital Transportation Marketplace by Logistics.com, FreightWise by Manugistics, Inc.); Web data mining [Cohen, Kelly, and Medaglia 2001]; Web-site personalization (Strategic Data Corp.).
Coping with complexity	The digital economy multiplies the decision complexity of the traditional economy with new technological options.	Combinatorial auction bid selection (Automated Credit Exchange [Ishikida et al. 2000], Bond Connect [Bossaerts, Fine, and Ledyard 2000]); Content-delivery network operations (Akamai patent US06108703); Logistics operations (OptiFlow).
Coping with uncertainty	Accelerating technology-driven business innovation and change greatly amplify traditional sources of uncertainty.	Scenario-based forecasting (Financial Engines Investment Advisor); Mark-to-Future [Dembo et al. 2000]); Web server quality of service [Iyengar, Squillante, and Zhang 1999]; Yield management [Smith et al. 2001].
Achieving understanding	The digital economy's demands for action prompt decision making without benefit of the cold light of reason.	Most applications based on validated, symbolic models in the OR tradition.
Experimenting without risk	Accelerating technology-driven business innovation and change increase exposure to risk.	Fiber network planning [Horner 2000]; Investment portfolio analysis (Financial Engines Investment Advisor); Most applications based on predictive models in the OR tradition.
Automating recurrent decisions	Scalability and Web-user expectations drive operational automation in e-business.	Home Depot combinatorial auctions [Keskinocak and Tayur 2001]; Online lending (First Union Loan Arranger); Real-time marketing optimization (MarketSwitch Workstation); Real-time yield management (OptiYield-RT).

Table 1: The digital economy needs these particular strengths of OR. Nearly every application mentioned in this article illustrates one or more of them.

lifetime value of customers in specific populations, such as credit-card holders, subject to constraints on such considerations as near-term revenue and attrition. Business problems addressed include online customer acquisition, cross-selling, dynamic repricing, and retention.

In addition, important CRM firms which do not yet apply OR, such as Siebel Systems, have application-programming interfaces permitting the attachment of analytic applications to their platforms.

A closely related application of wide interest is Web-site personalization, tailoring Web-site content to individuals based on whatever the firm may know or be able to infer about them [Riecken 2000]. Some approaches, especially the offline segmentation-oriented methods used to drive online rules-based personalization, are highly data-intensive and often involve applying data mining to clickstream data [Mulvenna, Anand, and Büchner 2000]. (Mining clickstream data—records of individuals' navigational paths on the Web—is also popular for improving Web-site design and evaluating advertising campaigns [Cohen, Kelly, and Medaglia 2001].) AI-oriented computer-science professionals, rather than OR professionals, have been the main architects of personalization and recommendation systems [Schafer, Konstan, and Riedl forthcoming]. As with data mining, OR people can easily understand the technologies involved and may be able to add value by integrating them into decision-support systems.

Real-time OR. Decision technology embedded in software for e-business processes must often work in real time. This is true, for instance, for real-time CRM applications of the sort just discussed, since the very limited attention span of a live customer at a Web site or on a cell phone demands immediate response [Nelson 2000]. The same motive holds for some consumer financial applications, for interactive dynamic-pricing applications where bidding, pricing, or purchase negotiations occur in one or two user sessions, and for recommendation and preference-based Web-site personalization applications that track user activity and match it with other users' activity for predictive purposes. An example is the custom recommendation system used by Amazon's site. When a registered consumer visits, the site offers product recommendations based on personalization technology [Schafer, Konstan, and Riedl forthcoming] fed by multiple data sources such as the purchase patterns of "similar" consumers and explicit feedback from the buyer.

A different motive underlies the need for real-time operational decision support in the transportation industry and in mobile commerce: equipment and people in motion are changing state so fast that only a speedy response can be useful.

A supplier's online order-taking process illustrates a third motive for real-time performance. Customers usually ask when an order can be delivered. The supplier bases the available-to-promise answer on inventory, orders on hand, and possibly the current production schedule. If it cannot deliver the order soon enough, it may avert a lost sale by giving the capable-to-promise answer after rerunning the production-scheduling algorithm with the potential order included. For a large order, the supplier could extend the analysis to take account of spot-market or strategic-partner actions that might speed up delivery. Ideally, it should perform all calculations in real time to close the deal before the customer has a chance to check with a competitor.

In general, operational and even tactical batch-style OR applications will increasingly require conversion to real-time operation as business processes are automated to meet e-business requirements.

Achieving real-time capability requires models and solvers that reliably return good solutions in compute windows that may be very much shorter than desired. Heuristics or approximation algorithms are often necessary.

Some applications pose challenges beyond short compute windows. One is the possible need for stability in solution space across optimal (or near-optimal) solutions. For instance, it could be objectionable in a capable-to-promise application for revised production schedules to differ wildly for reasons that are essentially accidental to the reoptimization algorithm. There are several known approaches to promote solution-space stability. Another challenge concerns how to think about repetitive decision making with incomplete information. The most appropriate solver paradigm may invoke the notion of an online algorithm, more familiar in theoretical computer science than in OR. Such an algorithm must execute each time new data comes in, taking an action that might not be optimal in light of subsequent data. In the popular competitive-analysis approach [Borodin and El-Yaniv 1998], an algorithm's goodness is measured relative to the best possible performance of an algorithm that has complete knowledge of the future. There are other approaches, and open research challenges in real-time OR abound.

Implications for Practitioners

How can OR professionals best flourish in the new era? First, as always, by deeply understanding the organization. Second, by playing to the six strengths listed previously. Third, by improving their ability to execute e-business projects:

Stay current. Discovering opportunities for OR applications and discussing them convincingly with managers require a broad understanding of e-business processes and issues that is also deep in selected areas. This will not come easily. Stay current by reading thoughtful mainstream coverage of the digital economy, including *The Economist*, *Harvard Business Review*, and *The Wall Street Journal Interactive Edition*. Study reports from research services, such as Forrester Research, Inc. and Gartner Group. Follow such technology-oriented magazines as *Business 2.0*, *Computer*, *The Industry Standard*, and *Information Week*. Periodically scan Yahoo! Inc.'s Tech Full Coverage, a good general portal to other sources.

Study the new decision technologies. Responding effectively to new challenges and opportunities calls for an expanded technical repertoire. This means learning about such topics as auction design, constraint programming, data mining, dynamic pricing and revenue management, personalization and recommendation technologies, and real-time OR. Few of these are covered in standard OR curricula, a fact that warrants attention in academia. We have given sources for each of these.

Monitor such OR sites as INFORMS Online and e-Optimization.com for new developments and professional-education opportunities.

Study economics. Brush up on economics, especially microeconomics, so that you can follow pertinent work in this tradition and perhaps initiate the kind of hybrid studies we called for earlier in which methods from economics and OR are combined to produce e-business analyses that go beyond qualitative insights to solve real model instances. Unfortunately, microeconomics has not always been included as one of the foundations of OR education. For a refresher, read Luenberger's [1995] elegant *Microeconomic Theory*, whose viewpoint and development are closer to OR than similar books written by economists.

Study the new information technologies. Many OR practitioners program or work closely with programmers. Since online e-business applications often require fairly new computer languages and implementation architectures, some investment in this direction is appropriate. Study Bhargava and Krishnan's [1998] paper to learn how to use Web technologies and distributed computing to deploy OR applications, study Fraternali's [1999] paper and the tools he mentions to prepare for Web implementations that involve databases, read Maurer's [2000] and Sprott's [2000] articles to find out why component-level programming is so important, and read Ousterhout [1998] to see why scripting languages are so important. To upgrade your programming skills, you could learn a scripting language like Per1 or JavaScript for gluing components together. Those needing a system-programming language should consider Java, a very popular object-oriented language with excellent cross-platform mobility and good facilities for linking to networks and packaging applications as servers.

Learn to work on Internet time. Internet time is not a fiction. Universities do not usually operate at this pace, nor do most OR practitioners. Yet anyone who hopes to work in the e-business world needs to learn to do professional projects faster. Preferably much faster. That means tailoring analyses to the time available and setting realistic targets for solution quality. Recent graduates will either make their peace with these heresies or soon enough find themselves relieved of their torments. Producing to Internet-driven schedules also means aggressively exploiting Internet communications options beyond e-mail, and for implementations, duly considering using Internet standards to facilitate integration, buying rather than building software or software components, using high-level and rapid development tools [Bhargava, Sridhar, and Herrick 1999], and implementing solutions in ASP mode.

Following these suggestions should position OR professionals for deeper involvement with e-business projects—perhaps even to strike out as Internet-based consultants or entrepreneurs. The head of one small (three-person) optimization-based software vendor offered these candid comments:

"...When customers ask how many people we have, I usually say 'six', quickly adding some of our agents. The company is totally virtual, in that we all work from home. Communication is via e-mail. No commuting, flexible work hours. We do need that, by the way, as the globality of the Internet means that we have customers in all time zones. So, on Sunday afternoon for us, the Australians get back to work. . . We have customers in more than 20 countries. One of the key points of working via the Internet is that you can look a lot bigger than you really are. . . sales over the Internet are totally not-regulated. That is, as long as our customers download things (no hard CDs, user guides, etc.), officially there are no import/export requirements, forms to fill out, duties to be paid, etc. So, this saves a lot of work."

At the outset, we likened the advent of e-business to the Cambrian explosion about 540 million years ago, when but an instant of evolutionary time produced all the phyla from which today's animals descend. The explosively evolving e-business ecosystem creates numerous opportunities for many professions, most certainly including OR. But keep in mind that catastrophes can also occur, such as the Cretaceous-Tertiary boundary event 66 million years ago when about half of the species then known disappeared. Some pundits predict this sort of future for the e-business ecosystem after the financial markets finish taking their toll, and network effects destroy all but a few dominant players in many e-business markets or worsening security breaches destroy public and managerial confidence. Sober-headed OR may be able to help companies manage such catastrophic risks.

Such specters may come to pass in some degree, but the e-business genie can never be put back in the bottle. Surely the e-business mania will fade and e- prefixes will become passé as the online and offline economies fuse [Fry 2000]. Beyond that, we can be sure only that breathtaking change will continue. For OR to thrive in difficult times as well as good, it must adapt and evolve about as fast as the business ecosystem is changing. The key to that is a strong curiosity about e-business developments and a willingness to experiment with new hybrids of information and decision technology.

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ILOG software components (www.ilog.com/industries/ebusiness/)
InfoHarvest (www.infoharvest.com)

Information Rules Web site (www.inforules.com/teaching.htm)
Information Week (www.informationweek.com)
INFORMS Online (www.informs.org)
InterNetivity Inc. (www.internetivity.com)
Java (developer.java.sun.com/developer/onlineTraining/)
JavaScript (webopedia.internet.com/TERM/J/JavaScript.html)
John Galt Solutions, Inc. (www.forecastx.com)
Lumina Decision Systems, Inc. (www.lumina.com)
Manugistics, Inc. (www.manugistics.com)
Market Design Inc. (www.market-design.com)
MarketSwitch (www.marketswitch.com)
MathML (www.w3.org/Math/)
Meta Software Corporation (www.metasoftware.com)
Michael Trick's software compilation (mat.gsia.cmu.edu/Computer_Programs/)
Net Exchange (www.nex.com)
online lending (www.ilog.com/industries/finance/onlinelend.cfm)
open-source software (www.opensource.org)
OptiBid (www.logistics.com/static/static1-1.asp)
OptiFlow (www.logistics.com/static/static1-1.asp)
Optimal Retirement Planner (www.i-orp.com)
OptiStop (www.logistics.com/static/static2-1.asp)
OptiYield-RT (www.logistics.com/static/static2-1.asp)
OR-Objects (www.opsresearch.com/OR-Objects/index.html)
Perfect.com (www.perfect.com)
Perl (www.perl.com/pub)
personalization (www.personalization.com)
Prime@Vantage Optimizer (www.primeresponse.com/products/optimizer.html)
ProMiles Online (www.promilesonline.com)
PROS Revenue Management, Inc. (www.prosrm.com)
Sabre Inc. (www.sabre.com)
SAS Institute (www.sas.com)
Siebel Systems (www.siebel.com)
SIMUL8 Corporation (www.SIMUL8.com)
SmartSettle (www.smartsettle.com)
StatBeans (www.sgcorp.com/statbeans.htm)
StatLib (lib.stat.cmu.edu)
StatPages.net (www.statpages.net)
StatPoint Internet Statistical Computing Center (www.sgcorp.com/on-line_computing.htm)
SticiGui (www.stat.Berkeley.EDU/~stark/SticiGui/index.htm)
Strategic Data Corp. (www.strategicdatacorp.com)
ThreadTec, Inc. (www.threadtec.com)
Trajecta, Inc. (www.trajecta.com)
TreeAge Software, Inc. (www.treeage.com)
Vanguard Software Corporation (www.vanguardsw.com)
vendor-managed inventory (www.cpfr.org/Vendor-Managed.html)
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