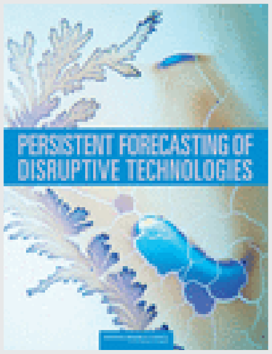
THE NATIONAL ACADEMIES PRESS

This PDF is available at http://nap.edu/12557

SHARE



Persistent Forecasting of Disruptive Technologies

DETAILS

136 pages | 8.5 x 11 | null
ISBN null | DOI 10.17226/12557

AUTHORS

Committee on Forecasting Future Disruptive Technologies; National Research Council

BUY THIS BOOK

FIND RELATED TITLES

Visit the National Academies Press at NAP.edu and login or register to get:

– Access to free PDF downloads of thousands of scientific reports
– 10% off the price of print titles
– Email or social media notifications of new titles related to your interests
– Special offers and discounts

Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press. (Request Permission) Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.

Copyright © National Academy of Sciences. All rights reserved.

PERSISTENT FORECASTING OF DISRUPTIVE TECHNOLOGIES

Committee on Forecasting Future Disruptive Technologies

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

Copyright National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This is a report of work supported by contract No. HHM40205D0011 between the Defense Intelligence Agency and the National Academy of Sciences. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-11660-2
International Standard Book Number-10: 0-309-11660-0

Limited copies are available from

Division on Engineering and Physical Sciences
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001
(202) 334-3118

Additional copies are available from

The National Academies Press
500 Fifth Street, N.W.
Lockbox 285
Washington, DC 20001
(800) 624-6242 or (202) 334-3313
(in the Washington metropolitan area)
http://www.nap.edu

Copyright 2010 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America

Copyright National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

COMMITTEE ON FORECASTING FUTURE DISRUPTIVE TECHNOLOGIES

GILMAN G. LOUIE, *Chair*, Alsop Louie Partners, San Francisco
PRITHWISH BASU, BBN Technologies, Cambridge, Massachusetts
HARRY BLOUNT, Blount Ventures, Hillsborough, California
RUTH A. DAVID, ANSER, Arlington, Virginia
STEPHEN DREW, Drew Solutions, Inc., Summit, New Jersey
MICHELE GELFAND, University of Maryland, College Park
JENNIE S. HWANG, H-Technologies Group, Cleveland, Ohio
ANTHONY K. HYDER, University of Notre Dame, Indiana
FRED LYBRAND, Elmarco, Inc., Chapel Hill, North Carolina
PAUL SAFFO, Saffo.com, Burlingame, California
PETER SCHWARTZ, Global Business Network, San Francisco
NATHAN SIEGEL, Sandia National Laboratories, Albuquerque, New Mexico
ALFONSO VELOSA, III, Gartner, Inc., Tuscon, Arizona

Staff

MICHAEL A. CLARKE, Lead DEPS Board Director
DANIEL E.J. TALMAGE, JR., Study Director
LISA COCKRELL, Mirzayan Policy Fellow, Senior Program Associate (until 8/10/2009)
ERIN FITZGERALD, Mirzayan Policy Fellow, Senior Program Associate (until 8/14/2009)
KAMARA BROWN, Research Associate
SARAH CAPOTE, Research Associate
SHANNON THOMAS, Program Associate

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

Preface

Technological innovations are key causal agents of surprise and disruption. These innovations, and the disruption they produce, have the potential to affect people and societies and therefore government policy, especially policy related to national security. Because the innovations can come from many sectors, they are difficult to predict and prepare for. The purpose of predicting technology is to minimize or eliminate this surprise. To aid in the development of forecasting methodologies and strategies, the Committee on Forecasting Future Disruptive Technologies of the National Research Council (NRC) was funded by the Director, Defense Research and Engineering (DDR&E) and the Defense Intelligence Agency's (DIA's) Defense Warning Office (DWO) to provide an analysis of disruptive technologies.

This is the first of two planned reports. In it, the committee describes disruptive technology, analyzes existing forecasting strategies, and discusses the generation of technology forecasts, specifically the design and characteristics of a long-term forecasting platform. In the second report, the committee will develop a hybrid forecasting method tailored to the needs of the sponsors.

As chairman, I wish to express our appreciation to the members of this committee for their earnest contributions to the generation of this first report. The members are grateful for the active participation of many members of the technology community, as well as to the sponsors for their support. The committee would also like to express sincere appreciation for the support and assistance of the NRC staff, including Michael Clarke, Daniel Talmage, Lisa Cockrell, Erin Fitzgerald, Kamara Brown, Sarah Capote, Carter Ford, and Shannon Thomas.

Gilman G. Louie, *Chair*
Committee on Forecasting Future Disruptive Technologies

Copyright National Academy of Sciences. All rights reserved.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Peter M. Banks, NAE, Astrolabe Ventures,
Andrew Brown, Jr., NAE, Delphi Corporation,
Natalie W. Crawford, NAE, RAND Corporation,
Thom J. Hodgson, NAE, North Carolina State University,
Anita K. Jones, NAE, University of Virginia,
Julie J. C. H. Ryan, George Washington University,
Kenneth W. Wachter, NAS, University of California, Berkeley, and
Ruoyi Zhou, IBM Almaden Research Center.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Maxine Savitz (NAE), Honeywell (retired). Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Copyright National Academy of Sciences. All rights reserved.

Contents

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

APPENDIXES

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

Acronyms and Abbreviations

ARG	alternate reality games
BOINC	Berkeley Open Infrastructure for Network Computing
CAS	complex adaptive system
DARPA	Defense Advanced Research Projects Agency
DDR&E	Director, Defense Research and Engineering
DNA	deoxyribonucleic acid
DoD	Department of Defense
DWO	Defense Warning Office
EC2	elastic compute cloud
ETL	extract, transform, and load
GDP	gross domestic product
GPS	Global Positioning System
GUI	graphical user interface
HD	high definition
IC	intelligence community
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IFTF	Institute for the Future
MCF	meta content framework
MEMS	microelectromechanical systems
MMORPG	massive multiplayer online role-playing game

Copyright National Academy of Sciences. All rights reserved.

NaCTeM	National Center for Text Mining
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NGO	nongovernmental organization
NORA	Nonobvious Relationship Awareness
NRC	National Research Council
NSF	National Science Foundation
PC	personal computer
PCR	polymerase chain reaction
QDR	quadrennial defense review
R&D	research and development
RDB	relational database
RDF	resource description framework
S3	Simple Storage Service
SAS	Statistical Analysis Software
SIMS	School of Information Management and Systems, University of California at Berkeley
SMT	simultaneous multithreading
TIGER	Technology Insight–Gauge, Evaluate, and Review
T-REX	The RDF Extractor, a text mining tool developed at the University of Maryland
TRIZ	Rus: *Teoriya Resheniya Izobretatelskikh Zadatch* (“inventor’s problem-solving theory”)
U.S.	United States
WWII	World War Two

Copyright National Academy of Sciences. All rights reserved.

Glossary

Backcasting Explores a future scenario for potential paths that could lead from the present to the forecast future.

Breakthrough Discovery or technology that changes a fundamental understanding of nature or makes possible something that previously seemed impossible (or improbable).

Catalyst Technology that alters the rate of change of a technical development or alters the rate of improvement of one or more technologies.

Chaos theory Characterizes deterministic randomness, which indeed exists in the initial stages of technology phase transition.

Delphi method Structured approach to eliciting forecasts from groups of experts, with an emphasis on producing an informed consensus view of the most probable future.

Disruption Event that significantly changes or interrupts movement or a process, trend, market, or social direction (Source: Dictionary.com).

Disruptive technology Innovative technology that triggers sudden and unexpected effects. The term was first coined by Bower and Christensen in 1995 to refer to a type of technology that brings about a sudden change to established technologies and markets (Bower and Christensen, 1995). Because these technologies are characteristically hard to predict and occur infrequently, they are difficult to identify or foresee.

Enhancer Technology that modifies existing technologies, allowing a measure of interest in the technologies to cross a critical threshold or tipping point.

Enabler Technology that makes possible one or more new technologies, processes, or applications.

Extrapolation Use of techniques such as trend analyses and learning curves to generate forecasts.

Forecasting bias Incompleteness in the data sets or methodologies used in a forecasting system (meaning in this report).

Genius forecast Forecast by a single expert who is asked to generate a prediction based on his or her intuition.

Copyright National Academy of Sciences. All rights reserved.

Ignorance Lack of knowledge or information. Ignorance contributes to bias in a forecast, which in turn can cause surprise.
Individual bias Prejudice held by a human being.
Influence diagram Compact graphical or mathematical representation of the decision-making process.
Intuitive view Opinion that the future is too complex to be adequately forecast using statistical techniques but should instead rely primarily on the opinions or judgment of experts.

Long-term forecasts Forecasts of the deep future (10 or more years from the present).

Measurement of interest Key characteristic that can be monitored to anticipate the development of disruptive technologies and applications.
Medium-term forecasts Forecasts of the intermediate future (typically 5 to 10 years from the present).
Morpher Technology that creates one or more new technologies when combined with another technology.

Persistent forecast Forecast that is continually improved as new methodologies, techniques, or data become available.

Scenario Tool for understanding the complex interaction of a variety of forces that can influence future events (meaning in this report).
Short-term forecasts Forecasts that focus on the near future (5 years or less from the present).
Signal Piece of data, a sign, or an event that is relevant to the identification of a potentially disruptive technology.
Signpost Recognized and actionable potential future event that could indicate an upcoming disruption.
Superseder New, superior technology that obviates an existing technology by replacing it.
Surprise Being taken unawares by some unexpected event.[1]

Techno cluster Geographic concentration of interconnected science- and high-tech-oriented businesses, suppliers, and associated institutions.
Technological innovation Successful execution of a fundamentally new technology or key development in the performance of an existing product or service.
Technology forecasting Prediction of the invention, timing, characteristics, dimensions, performance, or rate of diffusion of a machine, material, technique, or process serving some useful purpose.[2]
Technology forecasting system Technologies, people, and processes assembled to minimize surprise triggered by emerging or disruptive technologies, in order to support decision making.
Tipping point Time at which the momentum for change becomes unstoppable (Walsh, 2007).
Trend extrapolation Forecasting method in which data sets are analyzed to identify trends that can provide predictive capability.
TRIZ A forecasting system that uses a set of rules, termed "laws of technological evolution," that describe how technologies change throughout their lifetimes because of innovation and other factors, resulting in the development of new products, applications, and technologies.

---

[1]Adapted from the Oxford English Dictionary, available at http://www.askoxford.com/concise_oed/ignorance?view=uk. Last accessed August 25, 2009.
[2]The committee modified the definition of Martino (1969) to reflect the evolving practice of technology forecasting; accordingly, it included the rate of diffusion, which is a critical element in modern forecasting, and defined technology to include materials.

Copyright National Academy of Sciences. All rights reserved.

Summary

CONTEXT

In *The Art of War*, written in the 6th century B.C., Sun Tzu described surprise:

> In conflict, direct confrontation will lead to engagement and surprise will lead to victory. Those who are skilled in producing surprises will win. Such tacticians are as versatile as the changes in heaven and earth.[1]

Novel technologies are one of the principal means of surprising enemies or competitors and of disrupting established ways of doing things. Military examples of surprise include the English longbow, the Japanese long lance torpedo, the American atomic bomb, stealth technologies, and the Global Positioning System (GPS). Commercial examples include the telephone (Bell), business computers (UNIVAC and IBM), mobile phones (Motorola), recombinant DNA technologies (Genentech), PageRank (Google), and the iPod (Apple).

Until the 1970s, technological innovation tended to come from a limited number of well-established "techno clusters" and national and corporate laboratories.[2] Today, the number of techno clusters and laboratories is growing rapidly everywhere. Policy makers are concerned with the emergence of high-impact technologies that could trigger sudden, unexpected changes in national economies or in the security and quality of life they enjoy and that might affect the regional, national, or global balance of power. As such, policy makers and strategic planners use technology forecasts in their planning.

The value of technology forecasting lies not in its ability to accurately predict the future but rather in its potential to minimize surprises. It does this by various means:

- Defining and looking for key enablers and inhibitors of new disruptive technologies,
- Assessing the impact of potential disruption,

[1]Available at http://www.mailsbroadcast.com/the.artofwar.5.htm. Last accessed March 3, 2009.

[2]A techno cluster refers to a science- and high-tech-oriented Porter's cluster or business cluster (available at http://www.economicexpert.com/a/Techno:cluster:fi.htm; last accessed May 6, 2009). A business cluster is a geographic concentration of interconnected businesses, suppliers, and associated institutions in a particular field. Clusters are considered to increase the productivity with which companies can compete, nationally and globally. The term "industry cluster," also known as a business cluster, a competitive cluster, or a Porterian cluster, was introduced, and the term "cluster" was popularized by Michael Porter in *The Competitive Advantage of Nations* (1990). Available at http://en.wikipedia.org/wiki/Business_cluster. Last accessed March 3, 2009.

Copyright National Academy of Sciences. All rights reserved.

- Postulating potential alternative futures, and
- Supporting decision making by increasing the lead time for awareness.

The Office of the Director of Defense Research and Engineering (DDR&E) and the Defense Intelligence Agency (DIA) Defense Warning Office (DWO) asked the National Research Council (NRC) to set up a committee on forecasting future disruptive technologies to provide guidance on and insight into the development of a system that could forecast disruptive technology. The sponsor recognizes that many of the enabling disruptive technologies employed by an enemy could potentially come out of nonmilitary applications. Understanding this problem, the sponsor asked the committee to pay particular attention to ways of forecasting technical innovations that are driven by market demand and opportunities. It was agreed that the study should be unclassified and that participation in it not require security clearances. The sponsor and the committee strongly believe that if a forecasting system were to be produced that was useful in identifying technologies driven by market demand, especially global demand, then it would probably have significant value to a broad range of users beyond the Department of Defense and outside the United States. The sponsor and the committee also believe that the creation of an unclassified system is crucial to their goal of eliciting ongoing global participation. The sponsor asked the committee to consider the attributes of "persistent" forecasting systems—that is, systems that can be continually improved as new data and methodologies become available. See Box S-1 for the committee's statement of task.

This report is the first of two requested by the sponsors. In this first report, the committee discusses how technology forecasts are made, assesses several existing forecasting systems, and identifies the attributes of a persistent disruptive forecasting system. The second report will develop forecasting options specifically tailored to needs of the sponsors.

It is important to note that the sponsor has not asked the committee to build and design a forecasting system at this time. Instead, the intent of this report is to look at existing forecasting methodologies, to discuss important attributes and metrics of a persistent system for forecasting disruptive technologies, and to examine and comment on selected existing systems for forecasting disruptive technologies.

In 2007, the sponsor contracted the development of a persistent forecasting system called X2 (the name was later changed to Signtific).[3] At the time of this writing, not enough data had been generated from this system to provide a meaningful analysis of potentially disruptive technology sectors. The characteristics of X2 are analyzed in depth in Chapter 6.

CHALLENGE OF SUCH FORECASTS

All forecasting methodologies depend to some degree on the inspection of historical data. However, exclusive reliance on historical data inevitably leads to an overemphasis on evolutionary innovation and leaves the user vulnerable to surprise from rapid or nonlinear developments. In this report, a disruptive technology is an innovative technology that triggers sudden and unexpected effects. A methodology that can forecast disruptive technologies must overcome the evolutionary bias and be capable of identifying unprecedented change. A disruptive event often arrives abruptly and infrequently and is therefore particularly hard to predict using an evolutionary approach. The technology that precipitates the event may have existed for many years before it has its effect, and the effect may be cascading, nonlinear, and difficult to anticipate.

New forecasting methods must be developed if disruptive technology forecasts are to be effective. Promising areas include applications from chaos theory; artificial neural networks; influence diagrams and decision networks; advanced simulations; prediction markets; online social networks; and alternate reality games.

[3] Signtific, originally known as the X2 project, is a forecasting system that aims to provide an innovative medium for discussing the future of science and technology. It is designed to identify the most important trends and disruptions in science and technology and their impacts on the larger society over the next 20 years. Signtific is built and run by the Institute for the Future (http://www.iftf.org/node/939).

Copyright National Academy of Sciences. All rights reserved.

BOX S-1
Statement of Task

The NRC will establish an ad hoc committee that will provide technology analyses to assist in the development of timelines, methodologies, and strategies for the identification of global technology trends. The analyses performed by the NRC committee will not only identify future technologies of interest and their application but will also assess technology forecasting methodologies of use both in the government and in other venues in an effort to identify those most useful and productive. The duration of the project is twenty-four months; two reports will be provided.

Specifically, the committee will in its first report:

- Compare and contrast attributes of technology forecasting methodologies developed to meet similar needs in other venues.
- Identify the necessary attributes and metrics of a persistent worldwide technology forecasting platform.*
- Identify data sets, sources, and collection techniques for forecasting technologies of potential value.
- Comment on the technology forecasting approach set forth by the sponsor.
  - — Comment on the Delta Scan data sets and/or other data sets provided by the sponsor.
- Describe effective “dashboard” techniques for forecasting scenarios.
- From real-time data provided by the sponsor:
  - — Select and comment on emerging technology sectors.
  - — Advise the sponsor on where and how emerging and persistent technologies trends might become disruptive.
  - — Provide rationale for selections and indicate what key aspects will influence the rate of development in each.

The first report will be provided 16 months from contract award. The committee’s second report will be delivered during the second year, and will expand and refine report one in light of subsequent information provided by the more complete technology analyses anticipated. The statement of task of the final report will be developed in the course of meetings of the NRC staff and sponsor and will be brought back to the NRC for approval.

*After discussion, the committee chose to use the word “system” instead of “platform” throughout the report, due to the fact that the term platform has developed different connotations over time. This change to the Statement of Task was agreeable to the sponsor.

OVERVIEW OF FORECASTING TECHNIQUES

The field of technology forecasting is relatively new, dating back to work from the RAND Corporation during the years immediately following World War II (WWII). One of the earliest methods employed was the Delphi method, a structured process for eliciting collective expert opinions on technological trends and their impacts (Dalkey, 1967). Gaming and scenario planning also emerged as important technology forecasting methods in the 1950s and dramatically increased in popularity during the 1970s. All of these methods, as well as other more quantitative methods, are in use today.

In general, current forecasting methods can be broken into four categories: judgmental or intuitive methods; extrapolation and trend analysis; models; and scenarios and simulation. The advent of ever more powerful computation platforms and the growing availability of electronic data have led to a steady increase in the use of quantita-

Copyright National Academy of Sciences. All rights reserved.

tive methods as part of the technology forecasting process. New Internet-based forecasting tools and methods are leveraging the power of open source applications, social networks, expert sourcing (using prescreened experts to make technology forecasts), and crowd sourcing (allowing public participation with no prerequisites).

The committee believes that there is no single perfect method for forecasting disruptive technologies. Each has its strengths and weaknesses. Before choosing one or more methodologies to employ, a forecaster should consider the resources that can be applied to the forecast (financial, technology, forecasting infrastructure, and human capital), the nature and category of the technology being forecasted, the availability of experts and willingness of the crowd to participate in a forecast, the time frame that the forecast must address, and how the stakeholders intend to use the forecast.

Several pioneering systems already exist that attempt to forecast technology trends, including TechCast, Delta Scan, and X2.[4] The committee chose to examine these platforms because they incorporate many of the committee-defined attributes of a well-designed disruptive technology forecasting system. Also, all three platforms are currently used by researchers and governments to aid in the forecasting of disruptive technologies—TechCast and X2 are used by the U.S. government and Delta Scan was developed for the government of the United Kingdom. The committee was briefed by the teams responsible for the systems. Analysis of these systems offers important insights into the creation of persistent forecasts:

- *TechCast (1998)*. Voluntary self-selecting of people who examine technology advances on an ad hoc basis. The system's strengths include persistence, quantification of forecasts, and ease of use.
- *Delta Scan (2005).* Part of the United Kingdom's Horizon Scanning Centre, organized with the goal of becoming a persistent system.
- *X2 (2007)*. Persistent system with a novel architecture, qualitative assessment, and integration of multiple forecasting techniques.

These existing systems demonstrate that ambitious and sophisticated systems can help anticipate new technologies and applications and their potential impact.

Forecasting systems such as X2/Signtific use a combination of techniques such as the Delphi method, alternative reality gaming, and expert sourcing to produce a forecast. Others such as TechCast[5] employ expert sourcing in a Web environment. Popular Science's Prediction Exchange (PPX)[6] combined crowd sourcing and predictive markets to develop technology forecasts.

ATTRIBUTES OF AN EFFECTIVE SYSTEM

The following are viewed by the committee as important attributes of a well-designed system for forecasting disruptive technologies. Most are covered more thoroughly in Chapter 5. Proactive bias mitigation is discussed in detail in Chapter 4.

- *Openness.* An open approach allows the use of crowd resources to identify potentially disruptive technologies and to help understand their possible impact. Online repositories such as Wikipedia and SourceForge.net have shown the power of public-sourced, high-quality content. Openness can also facilitate an understanding of the consumer and commercial drivers of technology and what disruptions they might produce. In a phenomenon that *New York Times'* reporter John Markoff has dubbed "inversion," many advanced

[4] In 2009, the name "X2" was changed to "Signtific: Forecasting Future Disruptions in Science and Technology."

[5] TechCast is a technology think tank pooling the collective knowledge of technology experts around the world to produce authoritative technology forecasts for strategic business decisions. TechCast offers online technology forecasts and publishes articles on emerging technologies. It has been online since 1998. TechCast was developed by William E. Halal and his associates at George Washington University. Available at http://www.techcast.org/.

[6] Popular Science's Prediction Exchange (PPX) is an online virtual prediction market run as part of the magazine's Web sites, where users trade virtual currency, known as POP$, based on the likelihood of a certain event being realized by a given date. The prediction market ran from June 2007 until May 2009. At its peak, PPX had over 37,000 users. Available at http://en.wikipedia.org/wiki/PPX.

Copyright National Academy of Sciences. All rights reserved.

technologies are now arriving first in the hands of the ordinary consumers, who are the largest market segment. These technologies then slowly penetrate smaller and more elite markets, such as large business or the military (Markoff, 1996). Openness in a forecasting process does not mean that all information should be open and shared. Information that affects national security or violates the proprietary rights or trade secrets of an individual, organization, or company is justifiably classified and has special data-handling requirements. Forecasters need to consider these special requirements as they design and implement a forecasting system.

- *Persistence.* In today's environment, planning cycles are highly dynamic, and cycle times can be measured in days instead of years. For this reason it is important to have a forecasting system that monitors, tracks, and reformulates predictions based on new inputs and collected data. A well-designed persistent system should encourage the continuous improvement of forecasting methodologies and should preserve historical predictions, forecasts, signals, and data. In doing so, forecasts and methodologies can be easily compared and measured for effectiveness and accuracy. Openness and persistence are synergistic: Open and persistent systems promote the sharing of new ideas, encourage new research, and promote interdisciplinary approaches to problem solving and technology assessment.
- *Transparency.* The contributors and users of the system need to trust that the system operators will not exploit personal or other contributed information for purposes other than those intended. The system should publish and adhere to policies on how it uses, stores, and tracks information.
- *Structural flexibility.* This should be sufficient to respond to complexity, uncertainty, and changes in technology and methodology.
- *Easy access.* The system should be easy to use and broadly available to all users.
- *Proactive bias mitigation.* The main kinds of bias are cultural, linguistic, regional, generational, and experiential. A forecasting system should therefore be implemented to encourage the participation of individuals from a wide variety of cultural, geographic, and linguistic backgrounds to ensure a balance of viewpoints. In many fields, technology is innovated by young researchers, technologists, and entrepreneurs. Unfortunately, this demographic is overlooked by the many forecasters who seek out seasoned and established experts. It is important that an open system include input from the generation most likely to be the source of disruptive technologies and be most affected by them.
- *Incentives to participate.*
- *Reliable data construction and maintenance*.
- *Tools to detect anomalies and sift for weak signals*. A weak signal is an early warning of change that typically becomes stronger when combined with other signals.
- *Strong visualization tools and a graphical user interface*.
- *Controlled vocabulary.* The vocabulary of a forecast should include an agreed-upon set of terms that are easy for both operators and users to understand.

BENCHMARKING A PERSISTENT FORECASTING SYSTEM

After much discussion, the committee agreed on several characteristics of an ideal forecast that could be used to benchmark a persistent forecasting system. The following considerations were identified as important for designing a persistent forecasting system:

- *Data sources.* Data must come from a diverse group of individuals and collection methods and should consist of both quantitative and qualitative data.
- *Multiple forecasting method.* The system should combine existing and novel forecasting methodologies that use both quantitative and qualitative techniques.
- *Forecasting team.* A well-managed forecasting team is necessary to ensure expert diversity, encourage public participation, and help with ongoing recruitment.
- *Forecast output.* Both quantitative and qualitative forecast data should be presented in a readily available, intuitive format.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

- *Processing tools.* The system should incorporate tools that assess impact, threshold levels, and scalability; detect outlier and weak signals; and aid with visualization.
- *System attributes.* The system should be global, persistent, open, scalable and flexible, with consistent and simple terminology; it should also support multiple languages, include incentives for participation, and be easy to use.
- *Environmental considerations.* Financial support, data protection, infrastructure support, and auditing and review processes must also be considered.

HOW TO BUILD A PERSISTENT FORECASTING SYSTEM

Building a persistent forecasting system can be a complex and daunting task. Such a system is a collection of technologies, people, and processes. The system being described is not a software-only system. It is important to understand both the power and the limits of current computer science and not try to force the computer to perform tasks that humans can perform better. Computers are great tools for raw data mining, automated data gathering ("spidering"), statistical computation, data management, quantitative analysis, and visualization. Humans are best at pattern recognition, natural language interpretation and processing, intuition, and qualitative analysis. A well-designed system leverages the best attributes of both human and machine processes.

The committee recommends that a persistent forecasting system be built in phases and over a number of years. Successful Web-based systems, for example, usually use a spiral development approach to gradually add complexity to a program until it reaches completion.

The committee outlined eight important steps for performing an effective persistent forecast for disruptive technologies. These steps include:

- Define the goals of the mission by understanding key stakeholders' objectives.
- Determine the scope of the mission by ascertaining which people and resources are required to successfully put the system together, and meet mission objectives.
- Select appropriate forecasting methodologies to meet the mission objectives given the requirements and the availability of data and resources. Develop and use methods to recognize key precursors to disruptions, identifying as many potential disruptive events as possible.
- Gather information from key experts and information sources using ongoing information-gathering processes such as assigning metadata, assessing data sources, gathering historical reference data, assessing and mitigating biases, prioritizing signals, and applying processing and monitoring tools.
- Prioritize forecast technologies by estimating their potential impact and proximity in order to determine which signals to track, necessary threshold levels, and optimal resource allocation methods.
- Optimize the tools used to process, monitor, and report outliers, potential sources of surprise, weak signals, signposts, and changes in historical relationships, often in noisy information environments.
- Develop resource allocation and decision-support tools that allow decision makers to track and optimize their reactions as the probabilities of potential disruptions change.
- Assess, audit, provide feedback, and improve forecasts and forecasting methodologies.

CONCLUSION

This is the first of two reports on disruptive technology forecasting. Its goal is to help the reader understand current forecasting methodologies, the nature of disruptive technologies, and the characteristics of a persistent forecasting system for disruptive technology. In the second report, the committee plans to summarize the results of a workshop which will assemble leading experts on forecasting, system architecture, and visualization, and ask them to envision a system that meets the sponsor requirements while incorporating the desired attributes listed in this report.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

REFERENCES

Dalkey, Norman C. 1967. *DELPHI*. Santa Monica, Calif.: RAND Corporation.
Markoff, John. 1996. I.B.M. disk is said to break billion-bit barrier. *New York Times*. April 15.
Sun, Tzu. 599-500 B.C. *The Art of War*. Edited and translated by Thomas Cleary, 1991. Boston: Shambhala Publications.

Copyright National Academy of Sciences. All rights reserved.

1

Need for Persistent Long-Term Forecasting of Disruptive Technologies

In 2005, the Director of Plans and Programs in the Office of the Director of Defense Research and Engineering (DDR&E) presented three reasons why disruptive technologies are of strategic interest to the DoD (Shaffer, 2005):

- Understanding disruptive technologies is vital to continued competitiveness.
- The potential for technology surprise is increasing as knowledge in the rest of the world increases.
- There is a need to stay engaged with the rest of world in order to minimize surprise.

The *Quadrennial Defense Review* (2006 QDR) of the DoD describes four approaches an enemy can use to challenge the military capabilities of the United States. These include a traditional strategy (conventional warfare), an irregular strategy (insurgencies), a catastrophic strategy (mass-destruction terror attack), and a disruptive strategy (technological surprise, such as a cyberattack or an antisatellite attack). The 2006 QDR went on to describe the introduction of disruptive technologies by international competitors who develop and possess breakthrough technological capabilities. Such an act is intended to supplant U.S. advantages and marginalize U.S. military power, particularly in operational domains. Before the 2006 QDR, the DoD did not have a strategy to address disruptive warfare. Given the cycle time of research and development (R&D), strategy and concept of operations development, and the cycle time of defense procurement, the sponsor felt it would be most useful to develop a method for forecasting disruptive technologies that might emerge within 10 to 20 years.

The sponsor recognizes that many of the disruptive technologies employed by an enemy may originate from nonmilitary applications. With this in mind, the sponsor asked the committee to pay particular attention to those applications and domains in which technical innovations are driven by market demands and opportunities. Specifically, the sponsor requested that a broad forecasting system be developed and that it should extend beyond military technologies. It was agreed that this study should not be classified and that participation on the committee should not require security clearances.

An earlier NRC report, *Avoiding Surprise in an Era of Global Technology Advances*, provided the intelligence community (IC) with a methodology for gauging the potential implications of emerging technologies (NRC, 2005). This methodology has been widely accepted as a tool for assessing potential future national security threats from these emerging technologies. As part of its ongoing relationship with the Standing Committee for Technology Insight–Gauge, Evaluate, and Review (TIGER), the IC found it needed to identify and evaluate systems that could help it to produce long-term forecasts of disruptive technologies. Box 1-1 presents the statement of task for this study.

Copyright National Academy of Sciences. All rights reserved.

BOX 1-1
Statement of Task

The NRC will establish an ad hoc committee that will provide technology analyses to assist in the development of timelines, methodologies, and strategies for the identification of global technology trends. The analyses performed by the NRC committee will not only identify future technologies of interest and their application but will also assess technology forecasting methodologies of use both in the government and in other venues in an effort to identify those most useful and productive. The duration of the project is twenty-four months; two reports will be provided.

Specifically, the committee will in its first report:

- Compare and contrast attributes of technology forecasting methodologies developed to meet similar needs in other venues.
- Identify the necessary attributes and metrics of a persistent worldwide technology forecasting platform.*
- Identify data sets, sources, and collection techniques for forecasting technologies of potential value.
- Comment on the technology forecasting approach set forth by the sponsor.
  — Comment on the Delta Scan data sets and/or other data sets provided by the sponsor.
- Describe effective "dashboard" techniques for forecasting scenarios.
- From real-time data provided by the sponsor:
  — Select and comment on emerging technology sectors.
  — Advise the sponsor on where and how emerging and persistent technologies trends might become disruptive.
  — Provide rationale for selections and indicate what key aspects will influence the rate of development in each.

The first report will be provided 16 months from contract award. The committee's second report will be delivered during the second year, and will expand and refine report one in light of subsequent information provided by the more complete technology analyses anticipated. The statement of task of the final report will be developed in the course of meetings of the NRC staff and sponsor and will be brought back to the NRC for approval.

---

*After discussion, the committee chose to use the word "system" instead of "platform" throughout the report, due to the fact that the term platform has developed different connotations over time. This change to the Statement of Task was agreeable to the sponsor.

The idea of creating a persistent forecasting system—that is, a system that is being continually updated and improved—grew out of the TIGER standing committee's concern that both the defense community and the IC are largely focused on potentially disruptive technologies that are expected in the near future. It is the committee's understanding that many of the list of such technologies were generated from workshops or surveys that were largely limited to experts, most of them older than 40, from Western, English-speaking countries (often the United States). As discussed later in this report, this method of forecasting may introduce a number of biases, and the committee asked if there might be a better way to forecast disruptive technologies. A goal of this committee is to develop a persistent forecasting methodology that will capture disruptive technologies that other forecasting methodologies might miss and that will describe the nature of the disruption when other methods might not.

If one were to ascertain the frequency with which a particular technology is mentioned, a plot such as that shown in Figure 1-1 would emerge. Technologies to the left, for which citations are frequent, are likely to already

Copyright National Academy of Sciences. All rights reserved.

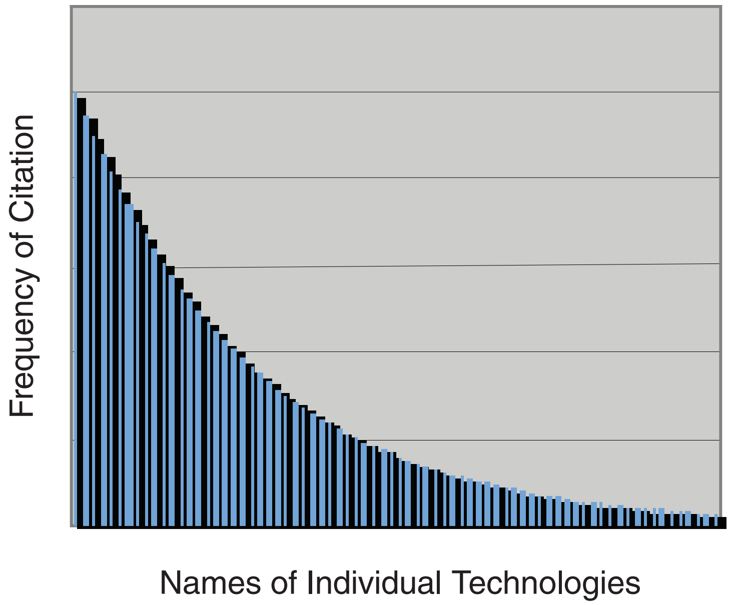


FIGURE 1-1 Curve showing the distribution of notional frequencies of citation for individual technologies.

be captured by traditional systems. The intent of this report is to develop a persistent forecasting system that can adequately identify the impact of technologies that are located in the tail of the distribution, on the far right side of the plot. A new, highly disruptive technology may be in this long tail either (1) because the magnitude of potential change it could produce is not appreciated and thus it is rarely cited or (2) because the market for the new technology is not obvious. The shift of aircraft propulsion from propeller to jet engine is an example of the first, while the rapid growth of the World Wide Web is an example of the second.

The challenge then becomes identifying potentially disruptive technologies in a sea of new technology innovations, applications, and discoveries. Compounding this challenge is the fact that some of the most disruptive technologies may emerge where no threat previously was known or even suspected, and that the ultimate impact may be the result of an integration of multiple existing technologies to create a new, highly disruptive application. These factors make it difficult for forecasters to determine important precursor signals of certain classes of disruptive technologies. New techniques and tools such as backcasting, contextual database searches, social networking analytical tools, interactive online gaming methodologies, alternative reality gaming, predictive markets, expected returns theory, portfolio and venture strategies, and visualization systems could improve signal development and identification.

RATIONALE FOR CREATING A NEW FORECASTING SYSTEM

As the world becomes more interconnected, small changes in one arena can trigger significant disruptions in others. Furthermore, decision makers in government, corporations, and institutions are faced with shrinking time frames in which to plan and react to disruptions. Traditional methodologies for forecasting disruptive technologies are generally incapable of predicting the most extreme scenarios, some of which may lead to the most potentially beneficial or catastrophic events. The committee believes the convergence of a number of advances—the increasing ubiquity of the Internet, the improving cost-efficiency of data storage and communications, the growing power of computation processing, and the globalization of trade and knowledge—has produced new tools and methods for forecasting emerging technologies that will bring about disruptions.

Copyright National Academy of Sciences. All rights reserved.

The committee believes there are at least five reasons to engage in a persistent forecasting exercise:

- To identify or develop methods and tools for the task of identification.
- To understand the potential disruptive impact of certain technologies.
- To increase the lead time for stakeholders to plan for and address potential disruptions.
- To give stakeholders tools to allocate resources in a manner that increases the probability of capitalizing on or mitigating the risk of a potential disruption.
- To provide data for early warning systems designed to detect the emergence of new and potentially disruptive technologies.

It should be made clear that early warnings of technological surprise cannot justify the suppression of knowledge, which the committee believes is not possible in any event. Instead, such early warnings are needed to prevent technological surprise and to promote adaptive investment flexibility.

HOW A DISRUPTIVE TECHNOLOGY DIFFERS FROM AN EMERGING TECHNOLOGY

Disruptive Versus Emerging Technologies

While the meaning of "emerging technology" is widely understood, that of "disruptive technology" may not be. The word "disruptive" connotes an interruption or upset to the orderly progression of an event, process, or activity. "Disruptive" can also imply confusion or disorder, or a drastic alteration in structure. In short, it entails a discontinuity. "Emerging" means rising up, coming into sight, and becoming apparent, important, or prominent. Something that is emerging can be just coming into existence, or beginning to become evident or obvious after a period of obscurity. While an emerging technology may become disruptive sometime, somewhere, its potential for such disruption may not have been recognized when it was first applied.

What Is a Disruptive Technology?

New technologies continue to emerge in every field and in very part of the world. In many cases, when a technology first emerges, its disruptive potential is not readily apparent. It is only later, once it has been applied or combined in an innovative way, that the disruption occurs. In other cases, however, a disruptive technology can truly be the result of a scientific or technological breakthrough. Some of these technologies are specific and target a niche market, while others possess the potential for widespread use and may open up new markets. A disruptive technology may change the status quo to such an extent that it leads to the demise of an existing infrastructure. Accordingly, three important questions should be asked about emerging technologies: Which of them could be considered latently disruptive? In which sector, region, or application would the technology be disruptive? What is the projected timeline for its implementation?

A scientific breakthrough can lead to not just a single disruption but to a series of them. The discovery of the electron in 1879 led to new technologies that were progressively more disruptive and caused long-lasting changes in the availability of products and services: Transistors (Figure 1-2), integrated circuits, and microprocessors (Figure 1-3) are the direct result of scientific and technical breakthroughs. Other advances are the result of an innovative application of existing technologies to new markets and problem sets: for example, Internet social networking Web sites (e.g., Facebook, MySpace, and LinkedIn), improvised explosive devices (IEDs), and portable digital music players such as the iPod (see Figure 1-4).

Some new technologies will cause shifts that change the world; others will remain laboratory curiosities that are never seen outside basic research centers. Still others will be something in between. Therefore, when examining a potentially disruptive technology, one must strive to understand how relevant it is. It is useful to factor in the scale of dissemination to ensure that the technology is truly disruptive.

The scale of dissemination can be clarified by looking at boundary conditions for the high-dissemination and low-dissemination cases:

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

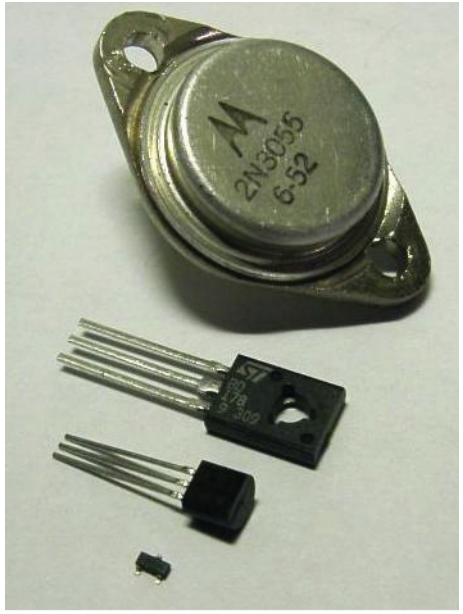


FIGURE 1-2 Assorted discrete transistors from Motorola and Siemens Technologies. SOURCE: Courtesy of Wikipedia. Used with permission from Daniel Ryde.

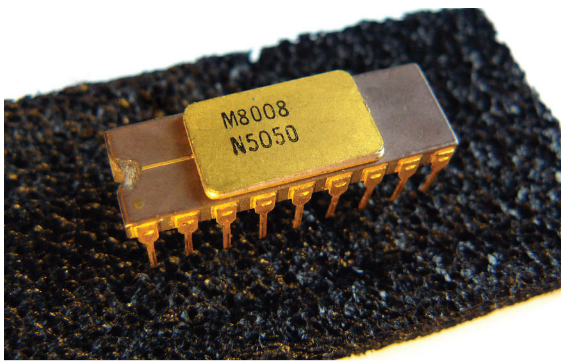


FIGURE 1-3 Microprocessor. SOURCE: Image courtesy of Paul James Ash and rarecpus.com.

- A high-dissemination technology can be easily replicated, with minimal infrastructure investments. Examples of this would be a new search engine algorithm or new encryption code, which could be replicated by copying information from one computer to another and would only require additional servers and storage systems.
- A low-dissemination technology or science can only be replicated with significant infrastructure investments. Examples of this include semiconductor technologies, which are created in large and expensive manufacturing facilities, and solar cell technologies, which will need massive capital investments to be able to compete with other alternative energy sources such as coal. If the infrastructure does not exist, the technology may be disseminated in isolated locations or communities, but few people will be able to leverage it.
- These boundary conditions may not apply to technologies that are targeted at a niche market—for example, flexible solar cells for hikers and the military. Weapons of mass destruction also fall into this category—for

Copyright National Academy of Sciences. All rights reserved.

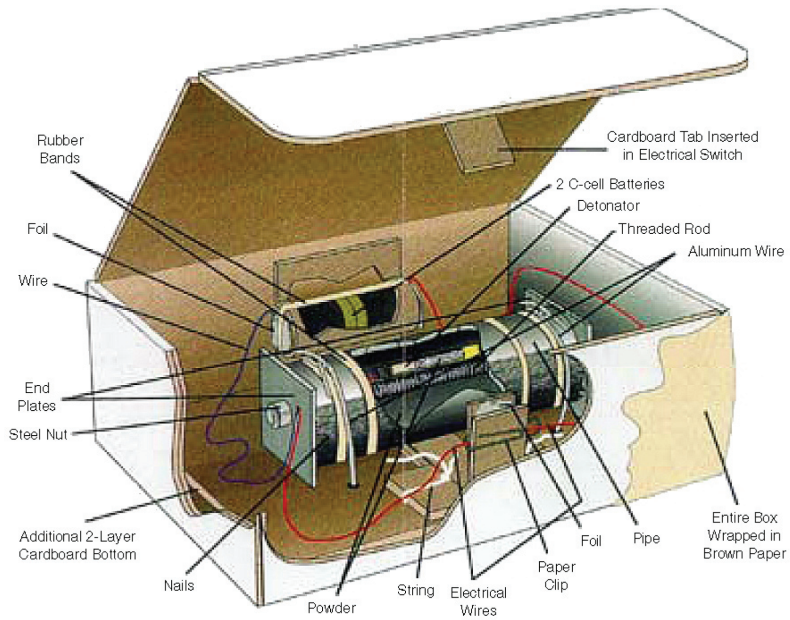


FIGURE 1-4 Improvised explosive device. SOURCE: GlobalSecurity.org.

example, biological agents that could affect a broad region. Here, even though its dissemination is limited, the technology may provide a differentiation, profitability, or impact out of proportion to its overall penetration in the society.

Forecasting Disruptive Technologies

The committee offers the following suggestions for the elements of a successful methodology for forecasting disruptive technologies.

Different Techniques Are Required

Techniques beyond those used to forecast emerging technologies will be required to forecast disruptive technologies. Such forecasting does not lend itself to techniques that rely on a linear progression of development or that require consensus from experts. In many cases, a technology is disruptive because few, if any, experts expected it to mature when it did or because they grossly misunderstood or underestimated its impact or applications.

Include a Broad Spectrum of Expertise

The committee believes it will be important to engage a wide variety of researchers, entrepreneurs, technologists, and scientists in any forecast. Since the sponsor wants a forecast that looks 10-20 years into the future, the committee feels it is important to include younger researchers, technologists, entrepreneurs, and scientists, who are most likely to create, and be affected by, these future disruptive technologies. The idea can be tested by surveying the demographics of the participants in a forecasting system. The system would need to have a way to track responses across demographic segments to assess the variation between age cohorts and determine how they would impact a forecast. If nothing else, the results of such an assessment should help inform forecasters about the fields of research being pursued by younger generations of researchers, technologists, scientists, and entrepreneurs.

Copyright National Academy of Sciences. All rights reserved.

Look Beyond Domestic Expertise

The committee observed that the defense and intelligence communities draw almost entirely on the opinion of domestic scientific and technical experts when performing forecasts. There is concern that these forecasts may be culturally biased and therefore could lead to the creation of blind spots. Given the impact of globalization, the increasing numbers of overseas research centers and universities, and significant increases in worldwide R&D investments, the committee recognizes the importance of surveying other cultures and regions and believes it is important to engage participants from other cultures in their native languages and familiar environments. The committee also recognizes that disruptive technologies do not disrupt all cultures and regions to the same extent or in the same way, so it is vital to understand how specific technologies may uniquely impact a region, country, or culture.

Wild Card Predictions Play an Important Role

A persistent forecasting system must look beyond the central mass of potential changes in technology, needs, or market drivers that have a modest to high probability of occurring. The system must identify conjunctions of science, technology, and needs that can drive innovations that might have a low probability of emerging owing to either daunting technical challenges or poor prospects for marketability but that could have a high impact if they were put into practice and adopted. These unlikely-to-emerge but potentially-high-impact innovations are sometimes referred to as wild cards. Without sacrificing scientific plausibility, the forecast must identify and evaluate wild card ideas to determine their potential for having a transformative, disruptive impact.

The ability of the human mind to draw conclusions about transformation where science and technology converge with need and opportunity is not well understood. Wild card concepts may be identified from both conventional sources (for example, research and product/process development) and unconventional sources (for example, contextual immersion in online gaming, virtual discussions on technical blogs, ideas from science fiction, the serendipitous results of searches in the library or on the Internet). New low-probability/high-impact wild card ideas may emerge less frequently in peer-reviewed scientific publications than through informal peer-to-peer discussions (for example, summaries of symposium discussions and workshops), team-based interactions (e.g., Internet gaming, simulations, blogs), and popular literature (science fiction, novels, television, and movies). Of particular interest will be a scientifically sound concept that is technically difficult but still possible yet not socially or commercially feasible without a transformation in attitudes, the market, or the culture.

Forecast Beyond the Defense and Intelligence Sectors

While the sponsors of this study are the U.S. Department of Defense (DoD) and the intelligence community (IC), the committee believes there are several compelling reasons not to limit the forecast to the defense- and intelligence-related sectors:

- One cannot predict all the potential uses of a technology. In many cases, a technology may have its greatest impact when used in a way that is very different from that which was originally intended; second-order effects are even more speculative. An example of this is the global positioning system (GPS). Originally developed by the DoD to meet military requirements, GPS was quickly adopted by the civilian world even before the system was completely operational.[1] Today, GPS is used for many applications never imagined by its creators, such as personal locators for Alzheimer's patients and pets, geocaching for treasure hunters and gamers, photo geotagging, performance measurement for sports and fitness enthusiasts, navigation systems for cell phones, and fleet management for truckers.
- Often the most disruptive effects arise from the integration of two or more well-understood technologies to create a new, highly disruptive technology or application. These types of disruptive technologies or

[1]Available at http://www.rand.org/pubs/monograph_reports/MR614/MR614.appb.pdf. Accessed April 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

applications may emerge from a convergence of resources or from technologies where no correlation had previously been identified. Examples of this phenomenon include the modern Internet, smartphones, personal computers, improvised explosive devices (IEDs), portable digital music players, and digital photography.

The committee recognizes how quickly forecasts, especially long-term forecasts, become obsolete. New information, discoveries, and scientific breakthroughs can quickly change a prediction from unlikely to inevitable. If a forecast is to have value it needs to be kept as current as possible and as dynamic as the domains it is covering.

USEFUL FORECASTS

A useful forecast provides insights that lead to effective action in the present. A forecast user must have confidence in the quality of the underlying data and in the analysis that led to the forecast. Success is measured not by how many accurate predictions a forecast makes, but by the value of its insights. A useful disruptive forecast reduces surprise; it alerts decision makers and provides them with the tools needed to avoid unanticipated and perhaps catastrophic outcomes.

It is also important to make a distinction between a vision (a forecast of a potential future state of reality described in a vague way, e.g., elimination of the gas power combustion engine for passenger vehicles); a measurement of interest (e.g., the energy stored per unit mass); a signpost (a recognized and actionable potential future event, e.g., the commercial availability of a battery that simultaneously surpasses gasoline in energy stored per unit of mass, energy stored per unit volume, and the price per unit of energy stored); and a signal (a piece of data, sign, or event that is relevant to the identification of a potentially disruptive technology—for example, Apple, Inc., placing a large order for new touch capacitance screens from a Chinese supplier). These concepts are critical for being able to discuss the comprehensiveness of forecasts and what one might hope to accomplish with better techniques (Strong et al., 2007).

Tools as Signposts

The appearance of enabling tools is an important signpost and signal. Technology is the result of engineering, and tools enable engineering. Often, the emergence of disruptive technologies is preceded by the appearance of enabling new tools. Examples of this include the following:

- Tools that perform nanoscale manipulation are enabling the rapid development of nanotechnology.
- Biological analytical tools built using microfluidic technologies enable the study of proteomics, genomics, and cellomics.
- The World Wide Web and blogs are tools enabling online social networking.

It should be recognized that many enabling tools are, in and of themselves, disruptive technologies. A useful forecasting exercise is to ask what other technologies could be envisioned once a new tool is predicted.

Those forecasting a disruptive technology should use reasoned analysis and seek expert advice to understand what foundational technologies and tools are required to engineer a new innovation. Estimating the timing of disruptive technologies requires understanding the sequence of foundational technologies and enabling tools and estimating when they will emerge.

Tipping Points as Signpoints

Tipping points, “the levels at which the momentum for change becomes unstoppable” (Walsh, 2007), are especially important to look for. Malcolm Gladwell, who had earlier coined the phrase, defined it then in sociological terms: “the moment of critical mass, the threshold, the boiling point” (Gladwell, 2000). “Tipping point” may refer to the point at which an adopted technology reaches the critical mass, to a time when the manufacturer’s cost drops

Copyright National Academy of Sciences. All rights reserved.

low enough to cause a significant change in the pattern of consumption, perhaps even mass substitution, or to the moment something unique becomes common.[2]

REPORT STRUCTURE

This report is the first of two on the topic requested by the sponsors. In this first report, the committee discusses how technology forecasts are made, assesses the various systems investigated by the committee, and identifies the attributes of a persistent, long-term disruptive technology forecasting system. Chapter 2 of this report outlines the history of technology forecasting and describes current forecasting methodologies and approaches; it also helps to further define and provide metrics for a successful forecast. Chapter 3 describes the nature of disruptive technologies, suggests sectors where disruptive technology is likely to take place, and identifies disciplines of interest for future study. Chapter 4 discusses bias and other factors that can affect the validity of a forecast. Chapter 5 proposes an approach to developing an ideal persistent disruptive technology forecast. In Chapter 6, existing forecasting systems (including those specified in this report's statement of task) are benchmarked against the ideal system. Finally, the conclusion (Chapter 7) suggests a process to build a persistent forecasting system and lists its potential applications.

In the second report, the committee plans to summarize the results of a workshop that will have assembled experts on forecasting, system architecture, and visualization. The experts will have been asked to envision a system that meets the sponsor's requirements while incorporating the suggestions in this report.

REFERENCES

Published

Gladwell, Malcolm. 2000. *The Tipping Point: How Little Things Can Make a Big Difference*. London: Little, Brown and Company.

NRC (National Research Council). 2005. *Avoiding Surprise in an Era of Global Technology Advances*. Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11286. Last accessed November 5, 2008.

Strong, R., J. Ryan, D. McDavid, Y. Leung, R. Zhou, E. Strauss, J. Bosma, T. Sabbadini, D. Jarvis, S. Sachs, P. Bishop, and C. Clark. 2007. A new way to plan for the future. Proceedings of the 40th Hawaii International Conference on Systems Science.

Walsh, B. 2007. A green tipping point. *Time Magazine*. Available at http://www.time.com/time/world/article/0,8599,1670871,00.html. Accessed April 6, 2009.

Unpublished

Shaffer, Allan. 2005. Disruptive technology: An uncertain future. Available at http://www.docstoc.com/docs/889200/Disruptive-Technology-An-Uncertain-Future. Last accessed May 6, 2009.

[2]Available at http://en.wikipedia.org/wiki/Tipping_Point. Accessed April 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

2

Existing Technology Forecasting Methodologies

INTRODUCTION

Technology Forecasting Defined

If individuals from disparate professional backgrounds were asked to define technology forecasting, chances are that the responses would be seemingly unrelated. Today, technology forecasting is used widely by the private sector and by governments for applications ranging from predicting product development or a competitor's technical capabilities to the creation of scenarios for predicting the impact of future technologies. Given such a range of applications, it is no surprise that technology forecasting has many definitions. In the context of this report, it is "the prediction of the invention, timing, characteristics, dimensions, performance, or rate of diffusion of a machine, material, technique, or process serving some useful purpose.[1] This chapter does not specifically address disruptive technology forecasting but addresses instead the most common methods of general technology forecasting in use today and in the past.

A forecast is developed using techniques designed to extract information and produce conclusions from data sets. Forecasting methods vary in the way they collect and analyze data[2] and draw conclusions. The methods used for a technology forecast are typically determined by the availability of data and experts, the context in which the forecast will be used and the needs of the expected users. This chapter will provide a brief history of technology forecasting, discuss methods of assessing the value of forecasts, and give an overview of forecasting methodologies and their applications.

History

Technology forecasting has existed in one form or another for more than a century, but it was not until after World War II (WWII) that it began to evolve as a structured discipline. The motivation for this evolution was the U.S. government's desire to identify technology areas that would have significant military importance.

[1]The committee modified the original definition of Martino (1969) to reflect the evolving practice of technology forecasting, which included both the materials themselves and the rate of diffusion as critical elements.

[2]Data in this context could include statistics, facts, opinions, trends, judgments, and individual predictions.

Copyright National Academy of Sciences. All rights reserved.

In 1945, a report called *Toward New Horizons* was created for the U.S. Army Air Forces (von Karman, 1945). This report surveyed the technological development resulting from WWII, discussed the implications of that development, and suggested future R&D (Neufeld et al., 1997). *Toward New Horizons,* written by a committee chaired by Theodore von Karman, arguably represents the beginning of modern technology forecasting.

In the late 1940s, the RAND Corporation was created to assist the Air Force with, among other things, technology forecasting. In the 1950s and 1960s, RAND developed the Delphi method to address some of the weaknesses of the judgment-based forecasting methodologies of that time, which were based on the opinions of a panel of experts. The Delphi method offers a modified structured process for collecting and distilling the knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback (Adler and Ziglio, 1996). The development of the Delphi method marked an important point in the evolution of technology forecasting because it improved the value of an entire generation of forecasts (Linstone and Turoff, 1975). The Delphi method is still widely used today.

The use of technology forecasting in the private sector began to increase markedly during the 1960s and 1970s (Balachandra, 1980). It seems likely that the growing adoption of technology forecasting in the private sector, as well as in government agencies outside the military, helped to diversify the application of forecasts as well as the methodologies utilized for developing the forecasts. The advent of more powerful computer hardware and software enabled the processing of larger data sets and facilitated the use of forecasting methodologies that rely on data analysis (Martino, 1999). The development of the Internet and networking in general has also expanded the amount of data available to forecasters and improved the ease of accessing these data. Today, technology forecasting continues to evolve as new techniques and applications are developed and traditional techniques are improved. These newer techniques and applications are looked at later in this chapter.

DEFINING AND MEASURING SUCCESS IN TECHNOLOGY FORECASTING

Some would argue that a good forecast is an accurate forecast. The unfortunate downside of this argument (point of view) is that it is not possible to know whether a given forecast is accurate a priori unless it states something already known. Accuracy, although obviously desirable, is not necessarily required for a successful forecast. A better measure of success is the actionability of the conclusions generated by the forecast in the same way as its content is not as important as what decision makers do with that content.

Since the purpose of a technology forecast is to aid in decision making, a forecast may be valuable simply if it leads to a more informed and, possibly, better decision. A forecast could lead to decisions that reduce future surprise, but it could also inspire the organization to make decisions that have better outcomes—for instance, to optimize its investment strategy, to pursue a specific line of research, or to change policies to better prepare for the future. A forecast is valuable and successful if the outcome of the decisions based on it is better than if there had been no forecast (Vanston, 2003). Of course, as with assessing accuracy, there is no way to know whether a decision was good without the benefit of historical perspective. This alone necessitates taking great care in the preparation of the forecast, so that decision makers can have confidence in the forecasting methodology and the implementation of its results.

The development of a technology forecast can be divided into three separate actions:

- Framing the problem and defining the desired outcome of the forecast,
- Gathering and analyzing the data using a variety of methodologies, and
- Interpreting the results and assembling the forecast from the available information.

Framing the problem concisely is the first step in generating a forecast. This has taken the form of a question to be answered. For example, a long-range Delphi forecast reported by RAND in 1964 asked participants to list scientific breakthroughs they regarded as both urgently needed and feasible within the next 50 years (Gordon and Helmer, 1964).

In addition to devising a well-defined statement of task, it is also important to ensure that all concerned parties understand what the ultimate outcome, or deliverable, of the forecast will be. In many cases, the forecaster

Copyright National Academy of Sciences. All rights reserved.

and the decision maker are not the same individual. If a forecast is to be successful, the decision maker needs to be provided with a product consistent with what was expected when the process was initiated. One of the best ways to assure that this happens is to involve the decision maker in the forecasting, so he or she is aware of the underlying assumptions and deliverables and feels ownership in the process.[3]

Data are the backbone of any forecast, and the most important characteristic of a data set is its credibility. Using credible data increases the probability that a forecast will be valuable and that better decisions will be made from it. Data can come in a variety of forms, but the data used in forecasting are of two types: statistical and expert opinion. The Vanstons have provided criteria for assessing both data types before they are used in a forecast (Vanston and Vanston, 2004).

For statistical data, the criteria are these:

- *Currency*. Is the timeliness of the data consistent with the scope and type of forecast? Historical data are valuable for many types of forecasts, but care should be taken to ensure that the data are sufficiently current, particularly when forecasting in dynamic sectors such as information technology.
- *Completeness*. Are the data complete enough for the forecaster(s) to consider all of the information relevant to an informed forecast?
- *Potential bias*. Bias is common, and care must be taken to examine how data are generated and to understand what biases may exist. For instance, bias can be expected when gathering data presented by sources who have a specific interest in the way the data are interpreted (Dennis, 1987).
- *Gathering technique*. The technique used to gather data can influence the content. For example, subtle changes in the wording of the questions in opinion polls may produce substantially different results.
- *Relevancy*. Does a piece of data have an impact on the outcome of the forecast? If not, it should not be included.

For data derived from expert opinion, the criteria are these:

- *Qualifications of the experts*. Experts should be carefully chosen to provide input to forecasts based on their demonstrated knowledge in an area relevant to the forecast. It should be noted that some of the best experts may not be those whose expertise or credentials are well advertised.
- *Bias*. As do statistical data, opinions may also contain bias.
- *Balance*. A range of expertise is necessary to provide different and, where appropriate, multidisciplinary and cross-cultural viewpoints.

Data used in a forecast should be scrutinized thoroughly. This scrutiny should not necessarily focus on accuracy, although that may be one of the criteria, but should aim to understand the relative strengths and weaknesses of the data using a structured evaluation process. As was already mentioned, it is not possible to ascertain whether a given forecast will result in good decisions. However, the likelihood that this will occur improves when decision makers are confident that a forecast is based on credible data that have been suitably vetted.

It is, unfortunately, possible to generate poor forecasts based on credible data. The data are an input to the forecast, and the conclusions drawn from them depend on the forecasting methodologies. In general, a given forecasting methodology is suited to a particular type of data and will output a particular type of result. To improve completeness and to avoid missing relevant information, it is best to generate forecasts using a range of methodologies and data.

Vanston offers some helpful discussion in this area (Vanston, 2003). He proposes that the forecast be arranged into five views of the future. One view posits that the future is a logical extension of the past. This is called an "extrapolation" and relies on techniques such as trend analyses and learning curves to generate forecasts. A contrasting view posits that the future is too complex to be adequately forecasted using statistical techniques, so it is likely

[3]John H. Vanston, Founder and Chairman of Technology Futures, Inc., personal communication with committee member Nathan Siegel in January 2008.

Copyright National Academy of Sciences. All rights reserved.

to rely heavily on the opinions or judgments of experts for its forecast. This is called an "intuitive" view. The other three views are termed "pattern analysis," "goal analysis," and "counter puncher." Each type of view is associated with a particular set of methodologies and brings a unique perspective to the forecast. Vanston and his colleagues propose that it is advantageous to examine the problem from at least two of the five views. This multiview approach obviously benefits from using a wider range of data collection and analysis methods for a single forecast. Because the problem has been addressed from several different angles, this approach increases the confidence decision makers can have in the final product. Joseph Martino proposed considering an even broader set of dimensions, including technological, economic, managerial, political, social, cultural, intellectual, religious, and ecological (Martino, 1983). Vanston and Martino share the belief that forecasts must be made from more than one perspective to be reasonably assured of being useful.

TECHNOLOGY FORECASTING METHODOLOGIES

As was discussed earlier, technology forecasting methodologies are processes used to analyze, present, and in some cases, gather data. Forecasting methodologies are of four types:

- Judgmental or intuitive methods,
- Extrapolation and trend analysis,
- Models, and
- Scenarios and simulations.

Judgmental or Intuitive Methods

Judgmental methods fundamentally rely on opinion to generate a forecast. Typically the opinion is from an expert or panel of experts having knowledge in fields that are relevant to the forecast. In its simplest form, the method asks a single expert to generate a forecast based on his or her own intuition. Sometimes called a "genius forecast," it is largely dependent on the individual and is particularly vulnerable to bias. The potential for bias may be reduced by incorporating the opinions of multiple experts in a forecast, which also has the benefit of improving balance. This method of group forecasting was used in early reports such as *Toward New Horizons* (von Karman, 1945).

Forecasts produced by groups have several drawbacks. First, the outcome of the process may be adversely influenced by a dominant individual, who through force of personality, outspokenness, or coercion would cause other group members to adjust their own opinions. Second, group discussions may touch on much information that is not relevant to the forecast but that nonetheless affects the outcome. Lastly, groupthink[4] can occur when forecasts are generated by groups that interact openly. The shortcomings of group forecasts led to the development of more structured approaches. Among these is the Delphi method, developed by the RAND Corporation in the late 1940s.

The Delphi Method

The Delphi method is a structured approach to eliciting forecasts from groups of experts, with an emphasis on producing an informed consensus view of the most probable future. The Delphi method has three attributes—anonymity, controlled feedback, and statistical group response[5]—that are designed to minimize any detrimental effects of group interaction (Dalkey, 1967). In practice, a Delphi study begins with a questionnaire soliciting input on a topic. Participants are also asked to provide a supporting argument for their responses. The questionnaires are collected, responses summarized, and an anonymous summary of the experts' forecasts is resubmitted to the

[4]Groupthink: the act or practice of reasoning or decision making by a group, especially when characterized by uncritical acceptance or conformity to prevailing points of view. Groupthink occurs when the pressure to conform within a group interferes with that group's analysis of a problem and causes poor decision making. Available at http://www.answers.com/topic/groupthink. Last accessed June 11, 2009.

[5]"Statistical group response" refers to combining the individual responses to the questionnaire into a median response.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

participants, who are then asked if they would care to modify their initial responses based on those of the other experts. It is believed that during this process the range of the answers will decrease and the group will converge toward a "correct" view of the most probable future. This process continues for several rounds, until the results reach predefined stop criteria. These stop criteria can be the number of rounds, the achievement of consensus, or the stability of results (Rowe and Wright, 1999).

The advantages of the Delphi method are that it can address a wide variety of topics, does not require a group to physically meet, and is relatively inexpensive and quick to employ. Delphi studies provide valuable insights regardless of their relation to the status quo. In such studies, decision makers need to understand the reasoning behind the responses to the questions. A potential disadvantage of the Delphi method is its emphasis on achieving consensus (Dalkey et al., 1969). Some researchers believe that potentially valuable information is suppressed for the sake of achieving a representative group opinion (Stewart, 1987).

Because Delphi surveys are topically flexible and can be carried out relatively easily and rapidly, they are particularly well suited to a persistent forecasting system. One might imagine that Delphi surveys could be used in this setting to update forecasts at regular intervals or in response to changes in the data on which the forecasts are based.

Extrapolation and Trend Analysis

Extrapolation and trend analysis rely on historical data to gain insight into future developments. This type of forecast assumes that the future represents a logical extension of the past and that predictions can be made by identifying and extrapolating the appropriate trends from the available data. This type of forecasting can work well in certain situations, but the driving forces that shaped the historical trends must be carefully considered. If these drivers change substantially it may be more difficult to generate meaningful forecasts from historical data by extrapolation (see Figure 2-1). Trend extrapolation, substitution analysis, analogies, and morphological analysis are four different forecasting approaches that rely on historical data.

Trend Extrapolation

In trend extrapolation, data sets are analyzed with an eye to identifying relevant trends that can be extended in time to predict capability. Tracking changes in the measurements of interest is particularly useful. For example, Moore's law holds that the historical rate of improvement of computer processing capability is a predictor of future performance (Moore, 1965). Several approaches to trend extrapolation have been developed over the years.

Gompertz and Fisher-Pry Substitution Analysis

Gompertz and Fisher-Pry substitution analysis is based on the observation that new technologies tend to follow a specific trend as they are deployed, developed, and reach maturity or market saturation. This trend is called a growth curve or S-curve (Kuznets, 1930). Gompertz and Fisher-Pry analyses are two techniques suited to fitting historical trend data to predict, among other things, when products are nearing maturity and likely to be replaced by new technology (Fisher and Pry, 1970; Lenz, 1970).

Analogies

Forecasting by analogy involves identifying past situations or technologies similar to the one of current interest and using historical data to project future developments. Research has shown that the accuracy of this forecasting technique can be improved by using a structured approach to identify the best analogies to use, wherein several possible analogies are identified and rated with respect to their relevance to the topic of interest (Green and Armstrong, 2004).

Green and Armstrong proposed a five-step structured judgmental process. The first step is to have an administrator of the forecast define the target situation. An accurate and comprehensive definition is generated based on

Copyright National Academy of Sciences. All rights reserved.

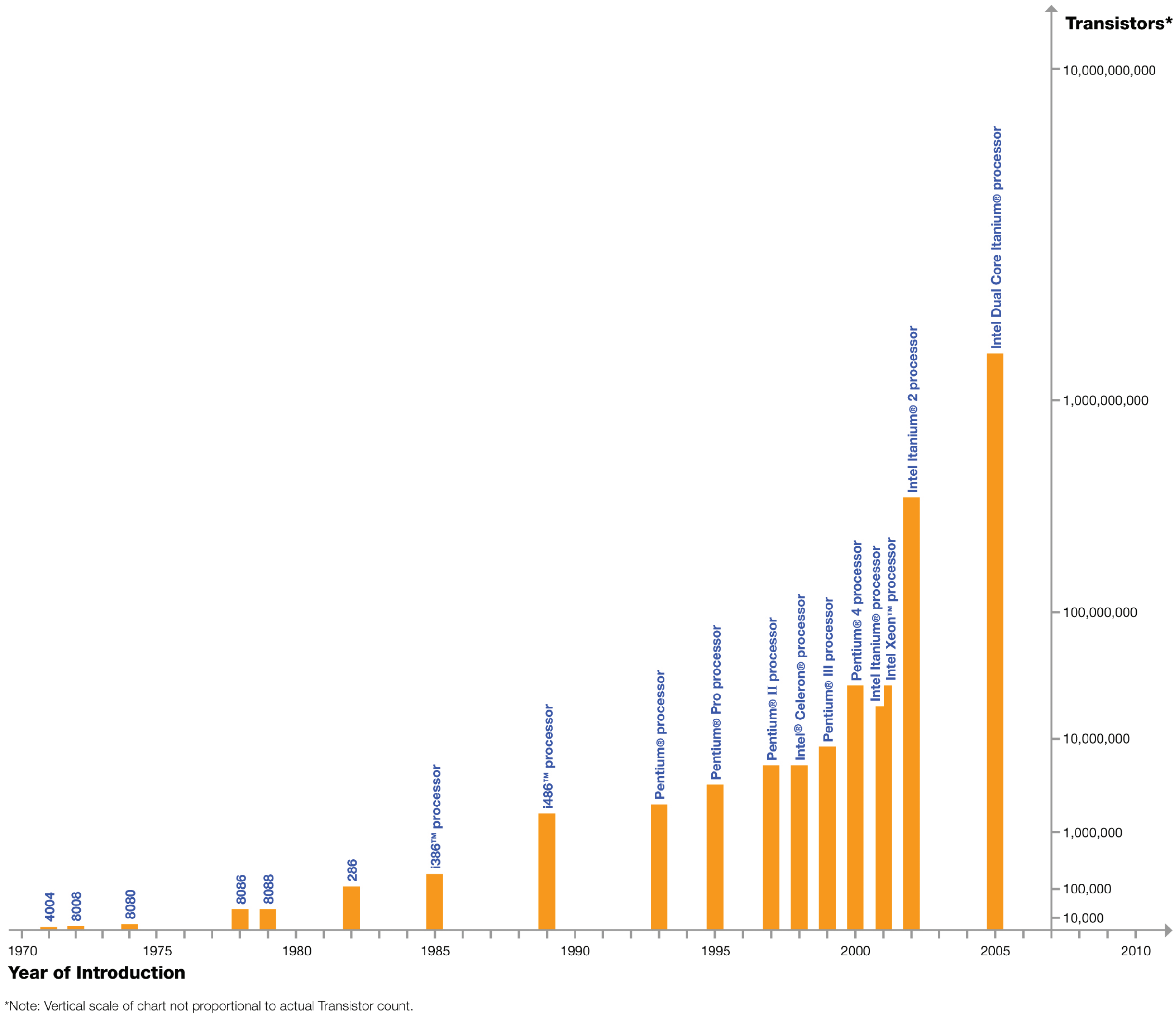


FIGURE 2-1 Moore's law uses trend analysis to predict the price and performance of central processing units. SOURCE: Available at http://www.cyber-aspect.com/features/feature_article~art~104.htm.

advice from unbiased experts or from experts with opposing biases. When feasible, a list of possible outcomes for the target is generated. The next step is to have the administrator select experts who are likely to know about situations that are similar to the target situation. Based on prior research, it is suggested that at least five experts participate (Armstrong, 2001). Once selected, experts are asked to identify and describe as many analogies as they can without considering the extent of the similarity to the target situation. Experts then rate how similar the analogies are to the target situation and match the outcomes of the analogies with possible outcomes of the target. An administrator would use a set of predefined rules to derive a forecast from the experts' information. Predefined rules promote logical consistency and replicability of the forecast. An example of a rule could be to select the analogy that the experts rated as the most similar to the target and adopt the outcome implied by that analogy as the forecast (Green and Armstrong, 2007).

Copyright National Academy of Sciences. All rights reserved.

Morphological Analysis (TRIZ)

An understanding of how technologies evolve over time can be used to project future developments. One technique, called TRIZ (from the Russian *teoriya resheniya izobretatelskikh zadatch,* or the "inventor's problem-solving theory"), uses the Laws of Technological Evolution, which describe how technologies change throughout their lifetimes because of innovation and other factors, leading to new products, applications, and technologies. The technique lends itself to forecasting in that it provides a structured process for projecting the future attributes of a present-day technology by assuming that the technology will change in accordance with the Laws of Technological Evolution, which may be summarized as follows:

- *Increasing degree of ideality*. The degree of ideality is related to the cost/benefit ratio. Decreasing price and improving benefits result in improved performance, increased functionality, new applications, and broader adoption. The evolution of GPS from military application to everyday consumer electronics is an example of this law.
- *Nonuniform evolution of subsystems*. The various parts of a system evolve based on needs, demands, and applications, resulting in the nonuniform evolution of the subsystem. The more complex the system, the higher the likelihood of nonuniformity of evolution. The development rate of desktop computer subsystems is a good example of nonuniform evolution. Processing speed, disk capacity, printing quality and speed, and communications bandwidth have all improved at nonuniform rates.
- *Transition to a higher level system*. "This law explains the evolution of technological systems as the increasing complexity of a product or feature and multi-functionality" (Kappoth, 2007). This law can be used at the subsystem level as well, to identify whether existing hardware and components can be used in higher-level systems and achieve more functionality. The evolution of the microprocessor from Intel's 4004 into today's multicore processor is an example of transition to a higher-level system.
- *Increased flexibility*. "Product trends show us the typical process of technology systems evolution is based on the dynamization of various components, functionalities, etc." (Kappoth, 2007). As a technology moves from a rigid mode to a flexible mode, the system can have greater functionality and can adapt more easily to changing parameters.
- *Shortening of energy flow path*. The energy flow path can become shorter when energy changes form (for example, thermal energy is transformed into mechanical energy) or when other energy parameters change. The transmission of information also follows this trend (Fey and Rivin, 2005). An example is the transition from physical transmission of text (letters, newspapers, magazines, and books), which requires many transformational and processing stages, to its electronic transmission (tweets, blogs, cellular phone text messaging, e-mail, Web sites, and e-books), which requires few if any transformational or processing stages.
- *Transition from macro- to microscale*. System components can be replaced by smaller components and microstructures. The original ENAIC, built in 1946 with subsystems based on vacuum tubes and relays, weighed 27 tons and had only a fraction of the power of today's ultralight laptop computers, which have silicon-based subsystems and weigh less than 3 pounds.

The TRIZ method is applied in the following stages (Kucharavy and De Guio, 2005):[6]

- *Analysis of system evolution*. This stage involves studying the history of a technology to determine its maturity. It generates curves for metrics related to the maturity level such as the number of related inventions, the level of technical sophistication, and the S-curve, describing the cost/benefit ratio of the technology. Analysis of these curves can help to predict when one technology is likely to be replaced by another.

[6]More information on the TRIZ method is available from http://www.inventioneeringco.com/. Last accessed July 21, 2009.

Copyright National Academy of Sciences. All rights reserved.

- *Roadmapping*. This is the application of the above laws to forecast specific changes (innovations) related to the technology.
- *Problem formulation*. The engineering problems that must be addressed to realize the evolutionary changes predicted in the roadmapping stage are then identified. It is in this stage that technological breakthroughs needed to realize future technologies are specified.
- *Problem solving*. Many forecasts would terminate in the problem formulation stage since it is generally not the purpose of a forecast to produce inventions. In spite of this, TRIZ often continues. This last stage involves an attempt to solve the engineering problems associated with the evolution of a technology. Although the attempt might not result in an actual invention, it is likely to come up with valuable information on research directions and the probability of eventual success in overcoming technological hurdles.

Models

These methods are analogous to developing and solving a set of equations describing some physical phenomenon. It is assumed sufficient information is available to construct and solve a model that will lead to a forecast at some time in the future; this is sometimes referred to as a "causal" model. The use of computers enables the construction and solution of increasingly complex models, but the complexity is tempered by the lack of a theory describing socioeconomic change, which introduces uncertainty. The specific forecast produced by the model is not as important as the trends it reveals or its response to different inputs and assumptions.

The following sections outline some model-based techniques that may be useful for forecasting disruptive technology. Some of them were used in the past for forecasting technology, with varying success.

Theory of Increasing Returns

Businesses that produce traditional goods may suffer from the law of diminishing returns, which holds that as a product becomes more commonplace, its marginal opportunity cost (the cost of foregoing one more unit of the next best alternative) increases proportionately. This is especially true when goods become commoditized through increased competition, as has happened with DVD players, flat screen televisions, and writable compact discs. Applying the usual laws of economics is often sufficient for forecasting the future behavior of markets. However, modern technology or knowledge-oriented businesses tend not to obey these laws and are instead governed by the law of increasing returns (Arthur, 1996), which holds that networks encourage the successful to be yet more successful. The value of a network explodes as its membership increases, and the value explosion attracts more members, compounding the results (Kelly, 1999). A positive feedback from the market for a certain technological product is often rewarded with a "lock-in." Google, Facebook, and Apple's iPhone and iPod are examples of this. A better product is usually unable to replace an older product immediately unless the newer product offers something substantially better in multiple dimensions, including price, quality, and convenience of use. In contrast, this does not happen in the "goods" world, where a slightly cheaper product is likely to threaten the incumbent product.

Although the law of increasing returns helps to model hi-tech knowledge situations, it is still difficult to predict whether a new technology will dislodge an older product. This is because success of the newer product depends on many factors, some not technological. Arthur mentions that people have proposed sophisticated techniques from qualitative dynamics and probability theory for studying the phenomenon of increasing returns and, thus, perhaps to some extent, disruptive technologies.

Chaos Theory and Artificial Neural Networks

Clement Wang and his colleagues propose that there is a strong relationship between chaos theory and technology evolution (Wang et al., 1999). They claim that technology evolution can be modeled as a nonlinear process exhibiting bifurcation, transient chaos, and ordered state. What chaos theory reveals, especially through bifurcation patterns, is that the future performance of a system often follows a complex, repetitive pattern rather than a linear process. They further claim that traditional forecasting techniques fail mainly because they depend

Copyright National Academy of Sciences. All rights reserved.

on the assumption that there is a logical structure whereby the past can be extrapolated to the future. The authors then report that existing methods for technology forecasting have been shown to be very vulnerable when coping with the real turbulent world (Porter et al., 1991).

Chaos theory characterizes deterministic randomness, which indeed exists in the initial stages of technology phase transition.[7] It is during this transition that a technology will have one of three outcomes: It will have a material impact, it will incrementally improve the status quo, or it will fail and go into oblivion. A particular technology exists in one of three states: (1) static equilibrium, (2) instability or a state of phase transition (bifurcation), and (3) bounded irregularity (chaos state). Bifurcations model sudden changes in qualitative behavior in technology evolution and have been classified as pitchfork bifurcation (gradual change, such as the switch from disk operating system [DOS] to Windows or the uniplexed information and computing system [UNIX]); explosive bifurcation (dramatic change, such as the digital camera disrupting the analog camera); and reverse periodic-adding bifurcation (dominant design, such as the Blu-ray Disc superseding the high-definition digital video disc [HD-DVD] format).

Wang and colleagues propose a promising mathematical model to aid in forecasting that uses a neural network to perform pattern recognition on available data sets. This model is useful because chaos is very sensitive to initial conditions. The basic methodology for applying artificial neural networks to technology forecasting follows these high-level steps: (1) preprocessing the data to reduce the analytic load on the network, (2) training the neural network, (3) testing the network, and (4) forecasting using the neural network. The proposed neural network model contains input and output processing layers, as well as multiple hidden layers connected to the input and output layers by several connections with weights that form the memory of the network. These are trained continuously when existing and historical data are run on the neural networks, perhaps enabling the detection of some basic patterns of technology evolution and improvement of the quality of forecasts.

It is possible to imagine utilizing some of these approaches for modeling disruptive technology evolution and forecasting future disruptions. They require, however, a great deal of validated data, such as the data available from the Institute for the Future (IFTF), to produce credible results.[8] Besides needing large and diverse validated training sets, artificial neural networks require significant computational power. Users of these networks should be mindful that these automated approaches could amplify certain biases inherent in the algorithms and to the data set for training. These networks can reinforce bias patterns found in the data and users, causing the network to produce unwarranted correlations and pattern identifications. It is important that both the algorithms and the data are reviewed frequently to reduce bias.

Influence Diagrams

An influence diagram (ID) is a compact graphical and mathematical representation of a decision situation.[9] In this approach, the cause-effect relationships and associated uncertainties of the key factors contributing to a decision are modeled by an interconnection graph, known as an influence diagram (Howard and Matheson, 1981). Such diagrams are generalizations of Bayesian networks and therefore useful for solving decision-making problems and probabilistic inference problems. They are considered improved variants of decision trees or game trees.

The formal semantics of an influence diagram are based on the construction of nodes and arcs, which allow specifying all probabilistic independencies between key factors that are likely to influence the success or failure of an outcome. Nodes in the diagram are categorized as (1) decision nodes (corresponding to each decision to be made), (2) uncertainty or chance nodes (corresponding to each uncertainty to be modeled), or (3) value or utility nodes (corresponding to the assigned value or utility to a particular outcome in a certain state), as shown in Figure 2-2. Arcs are classified as (1) functional arcs to a value node, indicating that one of the components of the additively separable utility function is a function of all the nodes at their tails; (2) conditional arcs to an uncertainty node, indicating that the uncertainty at their heads is probabilistically conditioned on all the nodes at their tails;

---

[7]"Technology phase transition" is the process in which one technology replaces another.

[8]An example of an influence diagram can be found at the IFTF Future Now Web site at http://www.iftf.org/futurenow. Last accessed October 28, 2008.

[9]Available at http://en.wikipedia.org/wiki/Influence_diagram. Last accessed July 15, 2009.

Copyright National Academy of Sciences. All rights reserved.

FIGURE 2-2 Example of an influence diagram. SOURCE: Adapted from Lee and Bradshaw (2004).

(3) conditional arcs to a deterministic node, indicating that the uncertainty at their heads is deterministically conditioned on all the nodes at their tails; and (4) informational arcs to a decision node, indicating that the decision at their heads is made with the outcome of all the nodes at their tails known beforehand.

In an influence diagram, the decision nodes and incoming information arcs model the alternatives; the uncertainty or deterministic nodes and incoming conditional arcs model the probabilistic and known relationships in the information that is available; and the value nodes and the incoming functional arcs quantify how one outcome is preferred over another. The *d*-separation criterion of Bayesian networks—meaning that every node is probabilistically independent of its nonsuccessor nodes in the graph given the outcome of its immediate predecessor nodes in the graph—is useful in the analysis of influence diagrams.

An influence diagram can be a useful tool for modeling various factors that influence technology evolution; however, its ability to accurately predict an outcome is dependent on the quality of values that are assigned to uncertainty, utility, and other parameters. If data can be used to help identify the various nodes in the influence diagrams and polled expert opinion can be funneled into the value assignments for uncertainty and utility, then a plethora of tools known to the decision theoretic community could be used to forecast a certain proposed event in future. The error bars in such forecasting will obviously depend on the quality of the values that capture the underlying interrelationships between the different factors and decision subprocesses.

Influence diagrams are an effective way to map and visualize the multiple pathways along which technologies can evolve or from which they can emerge. Forecasters can assess the conditions and likelihoods under which a technology may emerge, develop, and impact a market or system. By using the decision nodes and informational arcs as signposts, they can also use influence diagrams to help track potentially disruptive technologies.

Copyright National Academy of Sciences. All rights reserved.

Scenarios and Simulations

Scenarios are tools for understanding the complex interaction of a variety of forces that come together to create an uncertain future. In essence, scenarios are stories about alternative futures focused on the forecasting problem at hand. As a formal methodology, scenarios were first used at the RAND Corporation in the early days of the cold war. Herman Kahn, who later founded the Hudson Institute, pioneered their implementation as he thought through the logic of nuclear deterrence. His controversial book *On Thermonuclear War* was one of the first published applications of rigorous scenario planning (Kahn, 1960). The title of the follow-up edition, *Thinking About the Unthinkable*, suggests the value of the method—that of forcing oneself to think through alternative possibilities, even those which at first seem unthinkable (Kahn, 1962). It was a methodology particularly well suited to a surprise-filled world. Indeed, Kahn would often begin with a surprise-free scenario and take it from there, recognizing along the way that a surprise-free future was in fact quite unlikely.

In technology forecasting, scenarios have been used to explore the development paths of technologies as well as how they roll out into the world. The first case, using scenarios to anticipate development paths, entails a study of the fundamental science or engineering and its evolution, the tools needed to develop the technology, and the applications that will drive its economics. To forecast the future of the semiconductor while the technology was in its infancy required an understanding of solid state physics, silicon manufacturing, and the need for small guidance systems on U.S. missiles, all of which were critical to the early days of the microchip.

Using scenarios to forecast how technologies will play out in the real world calls for understanding the potential performance of the new technology and how users and other stakeholders will apply the technology. Early efforts to forecast the future of new technologies such as the personal computer, the cell phone, and the Internet missed the market because forecasters did not imagine that falling prices and network effects would combine to increase the value of the technology. These failed forecasts resulted in enormous business losses. IBM ultimately lost the personal computer market, and AT&T, despite its early dominance, never controlled the cell phone or the Internet market because it could not imagine the potential of the new technology. Xerox never capitalized on its pioneering work in graphical user interfaces (GUIs) because the company's management never saw how GUI could be combined with the revolution in personal computing to reshape the core of its document business (see Figure 2-3).

FIGURE 2-3 Xerox's Star system, which pioneered the GUI and the mouse. SOURCE: Image courtesy of Bruce Damer, DigiBarn Computer Museum, and Xerox Corporation.

Copyright National Academy of Sciences. All rights reserved.

In another approach, "backcasting," planners envision various future scenarios and then go back to explore the paths that could lead them there from the present,[10] examining the paths, decisions, investments, and breakthroughs along the way. Backcasting is a unique form of forecasting. Unlike many forecasting methods that begin by analyzing current trends and needs and follow through with a projection of the future, backcasting starts with a projection of the future and works back to the present. The grounding in the future allows the analysis of the paths from the present to a future to be more concrete and constrained.

Forecasting centering on backcasting would start by understanding the concerns of the stakeholders and casting those concerns in the context of alternative futures. Scenarios could then be envisioned that describe what the world would look like then: Sample scenarios could include a world without oil; wars fought principally by automated forces, drones, and robots; or a world with a single currency. Forecasters then would work backward to the present and generate a roadmap for the future scenario. The purpose of the backcast would be to identify signposts or tipping points that might serve as leading indicators. These signposts could be tracked with a system that alerts users to significant events much as Google News monitors the news for topics that interest users.

There are many challenges involved in executing an effective backcast. Matching the range of potential alternative futures with the range of stakeholder concerns is difficult but extremely important for making sure the backcast scenarios are relevant. The number of backcasts required for a forecast can become unwieldy, especially if there are numerous stakeholders with diverse needs and concerns and multiple pathways for arriving at a particular future. Backcasting requires an imaginative expert and/or a crowd base to generate truly disruptive scenarios and signposts.

Dynamic Simulations and War Games

Military leaders have attempted to simulate the coming battle as a training exercise since the earliest days of organized combat. The modern war games used in technology forecasting are another way of generating and testing scenarios. The military has war games and simulations to test new technologies and applications to better understand how they might change military strategy and tactics. War games are useful tools when human judgment plays an important role in how a technology is deployed. They test an engineered or technological capability that is then tested against the response of various actors who are actually played by live people and interact with one another over time to shape the outcome. For example, Monsanto might wish to simulate a political situation to anticipate the reaction to genetically modified seeds.[11] Careful selection of stakeholders involved in the simulation might inadvertently have anticipated adverse public reaction. A significant market opportunity would be lost if the company faces global opposition to its genetically modified rice.

Other Modern Forecasting Techniques

New capabilities and challenges lead to the creation of new forecasting techniques. For example, the ability of the Internet to create online markets has opened new ways to integrate judgment into a prediction market (see below for a definition). Meanwhile, the rapid advance of engineering in sometimes surprising directions, such as sensing and manipulating matter and energy at a nanometer scale, opens up major discontinuities in potential forecasts, posing particularly difficult problems. The committee suggests considering the following techniques for forecasting disruptive technologies.

Prediction Markets

Prediction markets involve treating the predictions about an event or parameter as assets to be traded on a virtual market that can be accessed by a number of individuals (Wolfers and Zitzewitz, 2004).[12] The final market

[10]Available from http://en.wikipedia.org/wiki/Backcasting. Last accessed May 6, 2009.
[11]Available from www.planetarks.org/monsanto/goingahead.cfm. Last accessed April 28, 2009.
[12]An example of a contemporary prediction market is available from http://www.intrade.com/. Last accessed October 28, 2008.

Copyright National Academy of Sciences. All rights reserved.

value of the asset is taken to be indicative of its likelihood of occurring. Because prediction markets can run constantly, they are well suited to a persistent forecasting system. The market naturally responds to changes in the data on which it is based, so that the event's probability and predicted outcome are updated in real time.

Prediction markets use a structured approach to aggregate a large number of individual predictions and opinions about the future. Each new individual prediction affects the forecasted outcome. A prediction market automatically recomputes a forecast as soon as a new prediction is put into the system. One advantage of prediction markets over other forecasting techniques such as the Delphi method is that participation does not need to be managed. The participants take part whenever they want, usually when they obtain new information about a prediction or gain an insight into it.

Prediction markets may benefit from other forecasting techniques that generate a signpost, such as backcasting and influence diagrams. Describing the signpost that appears when a particular point has been reached in a prediction market may help to encourage market activity around a prediction (Strong et al., 2007). One shortcoming of prediction markets is that it is difficult to formulate some forecasting problems in the context of a market variable. Some believe, moreover, that predictive markets are also not ideal for long-term disruptive technology forecasts, where uncertainty is high, probabilistic outcomes are very small (low probability), signals and signposts are sparse, and disruptions caused by technology and signposts can set in rapidly and nonlinearly (Graefe and Weinhardt, 2008).

Alternate Reality Games

With the advent of the ability to create simulated worlds in a highly distributed network, multiplayer system alternate realities have begun to emerge online. An example of an alternate reality game (ARG) is a simulation run by the Institute for the Future (IFTF), *World Without Oil* (Figure 2-4). Simulations like this can be used to

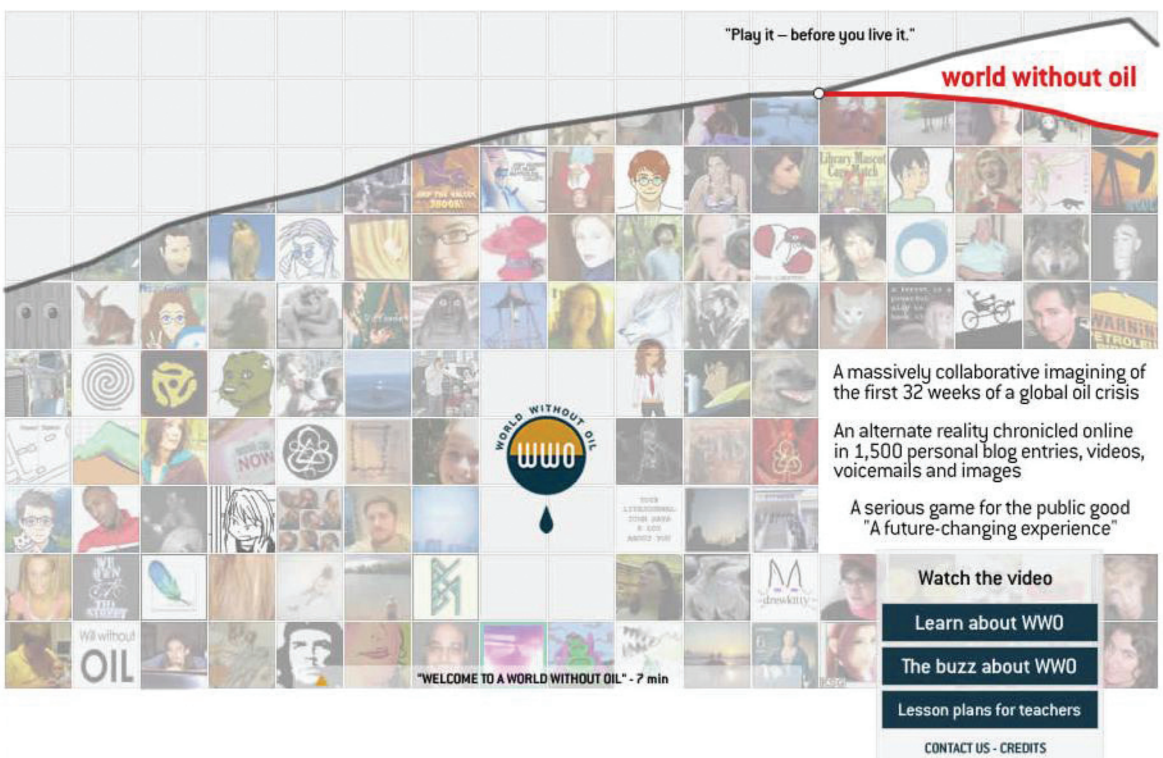


FIGURE 2-4 Screen shot from *World Without Oil*. SOURCE: Image courtesy of Ken Eklund, game designer, creative director, and producer.

Copyright National Academy of Sciences. All rights reserved.

test possibilities that do not yet exist. ARGs bring together scenarios, war games, and computer simulations in one integrated approach. Progress is made in ARGs when both first-order changes and second-order[13] effects are observed and recorded during game play. ARGs can enhance a forecast by revealing the impact of potential alternative future scenarios through game play and role playing.

Online Forecasting Communities

The Internet makes it possible to create online communities like prediction markets engaged in continuous forecasting activities. Techcast, a forecasting endeavor of George Washington University, a research project led by William E. Halal, has been online since 1998. It has developed into a service billing itself as a "virtual think tank" and is providing a range of services for a fee. Like any such service, its success depends on the quality of the individuals it brings together and its effectiveness in integrating their combined judgment. The endurance and continuing refinement of Techcast suggests it is becoming more useful with time.

Obsolescence Forecasting

Occasionally, major technologies are made obsolete by fundamental advances in new technology. The steam engine, for instance, gave way to electric motors to power factories, and the steamship eliminated commercial sailing. An interesting question about the future would be to ask how key current technologies might be made obsolete. Will the electric drive make the gasoline engine obsolete? Will broadcast television be made obsolete by the Internet? What would make the Internet, the cell phone, or aspirin obsolete? These are questions whose answers can already be foreseen. Asking them may reveal the potential for major discontinuities. Obsolescence forecasting can be considered a form of backcasting, because forecasters envision a scenario intruded on by an obsolescing technology, then explore how it happened.

Time Frame for Technology Forecasts

It is important to understand that the time frame for a forecast will depend on the type of technology as well as on the planning horizon of the decision maker. For example, decisions on software may move much faster than decisions on agricultural genetic research because of different development times and life cycles. Generally, the longer the time frame covered by a technology forecast, the more uncertain the forecast.

Short Term

Short-term forecasts are those that focus on the near future (within 5 years of the present) to gain an understanding of the immediate world based on a reasonably clear picture of available technologies. Most of the critical underpinning elements are understood, and in a large fraction of cases these forecasts support implementations. For example, a decision to invest in a semiconductor fabrication facility is based on a clear understanding of the technologies available within a short time frame.

Medium Term

Medium-term forecasts are for the intermediate future (typically within 5 to 10 years of the present) and can be characterized, albeit with some gaps in information, using a fairly well understood knowledge base of technology trends, environmental conditions, and competitive environments. These forecasts may emerge from ongoing research programs and can take into account understandings of current investments in manufacturing facilities or

[13]Second-order effects are the unintended consequences of a new technology that often have a more powerful impact on society than the more obvious first-order changes. Available at www.cooper.com/journal/2001/04/the_secondorder_effects_of_wir.html. Last accessed July 12, 2009.

Copyright National Academy of Sciences. All rights reserved.

expected outcomes from short-term R&D efforts. Assumptions derived from understanding the environment for a particular technology can be integrated into a quantitative forecast for the industry to use in revenue assessments and investment decisions.

Long Term

Long-term forecasts are forecasts of the deep future. The deep future is characterized by great uncertainty in how current visions, signposts, and events will evolve and the likelihood of unforeseen advances in technology and its applications. These forecasts are critical because they provide scenarios to help frame long-term strategic planning efforts and decisions and can assist in the development of a portfolio approach to long-term resource allocation.

While long-term forecasts are by nature highly uncertain, they help decision makers think about potential futures, strategic choices, and the ramifications of disruptive technologies.

CONCLUSION

Modern technological forecasting has only been utilized since the end of WWII. In the last 50 years, technology forecasts have helped decision makers better understand potential technological developments and diffusion paths. The range of forecasting methods has grown and includes rigorous mathematical models, organized opinions such as those produced by the Delphi method, and the creative output of scenarios and war games. While each method has strengths, the committee believes no single method of technology forecasting is fully adequate for addressing the range of issues, challenges, and needs that decision makers face today. Instead, it believes that a combination of methods used in a persistent and open forecasting system will improve the accuracy and usefulness of forecasts.

REFERENCES

Adler, M., E. Ziglio, eds. 1996. *Gazing into the Oracle: The Delphi Method and Its Application to Social Policy and Public Health*. London: Kingsley.

Armstrong, J.S. 2001. Combining forecasts. In J.S. Armstrong, ed., *Principles of Forecasting,* Boston, Mass.: Kluwer Academic Publishers.

Arthur, Brian W. 1996. Increasing returns and the new world of business. *Harvard Business Review* (July-August).

Balachandra, Ramaiya. 1980. Technological forecasting: Who does it and how useful is it? *Technological Forecasting and Social Change* 16: 75-85.

Dalkey, Norman C. 1967. *DELPHI*. Santa Monica, Calif.: RAND Corporation.

Dalkey, Norman C., Bernice B. Brown, and S.W. Cochran. 1969. *The Delphi Method, III: Use of Self-Ratings to Improve Group Estimates.* Santa Monica, Calif.: RAND Corporation.

Dennis, Robin L. 1987. Forecasting errors: The importance of the decision-making context. *Climatic Change* 11: 81-96.

Fey, Victor, and Eugene Rivin. 2005. *Innovation on Demand: New Product Development Using TRIZ*. New York: Cambridge University Press.

Fisher, J.C., and R.H. Pry. 1970. A simple substitution model of technological change. *Technological Forecasting and Social Change* 3(1): 75-78.

Gordon, Theodore J., and Olaf Helmer. 1964. *Report on a Long-Range Forecasting Study*. Santa Monica, Calif.: RAND Corporation.

Graefe, Andreas, and Christof Weinhardt. 2008. Long-term forecasting with prediction markets—A field experiment on applicability and expert confidence. *The Journal of Prediction Markets* 2(2): 71-91.

Green, Kesten C., and J. Scott Armstrong. 2004. Structured analogies for forecasting. Working Paper 17, Monash University Department of Econometrics and Business Statistics. September 16.

Green, Kesten C., and J. Scott Armstrong. 2007. Structured analogies for forecasting. *International Journal of Forecasting* 23(3): 365-376.

Howard, Ronald A., and James E. Matheson. 1981. Influence diagrams. Pp. 721-762 in *Readings on the Principles and Applications of Decision Analysis*, *vol. I* (1984), Howard, Ronald A., and James E. Matheson, eds., Menlo Park, Calif.: Strategic Decisions Group.

Copyright National Academy of Sciences. All rights reserved.

Kahn, Herman. 1960. *On Thermonuclear War*. Princeton, N.J.: Princeton University Press.

Kahn, Herman. 1962. *Thinking About the Unthinkable*. New York: Horizon Press.

Kappoth, Prakasan. 2007. Design features for next generation technology products. *TRIZ Journal*. Available at http://www.triz-journal.com/archives/2007/11/05/. Last accessed October 29, 2009.

Kelly, Kevin. 1999. *New Rules for the New Economy: 10 Radical Strategies for a Connected World*. New York: Penguin Books. Available at http://www.kk.org/newrules/index.php. Last accessed July 21, 2009.

Kucharavy, Dmitry, and Roland De Guio. 2005. Problems of forecast. Presented at ETRIA TRIZ Future 2005, Graz, Austria, November 16-18. Available at http://hal.archives-ouvertes.fr/hal-00282761/fr/. Last accessed November 11, 2008.

Kuznets, S. 1930. *Secular Movements in Production and Prices: Their Nature and Their Bearing on Cyclical Fluctuations*. Boston, Mass.: Houghton & Mifflin.

Lee, Danny C., and Gay A. Bradshaw. 2004. Making monitoring work for managers. Available at http://www.fs.fed.us/psw/topics/fire_science/craft/craft/Resources/Lee_Bradshaw_monitoring.pdf. Last accessed November 3, 2008.

Lenz, R.C. 1970. Practical application of technical trend forecasting. In *The Science of Managing Organized Technology*, M.J. Cetron and J.D. Goldhar, eds., New York: Gordon and Breach, pp. 825-854.

Linstone, Harold A., and Murray Turoff. 1975. *The Delphi Method: Techniques and Application*. Reading, Mass.: Addison-Wesley.

Martino, Joseph P. 1969. *An Introduction to Technological Forecasting*. London: Gordon and Breach Publishers.

Martino, Joseph P. 1983. *Technological Forecasting for Decision Making*. Amsterdam, The Netherlands: North-Holland Publishing.

Martino, Joseph P. 1987. Recent developments in technological forecasting. *Climatic Change* 11: 211-235.

Martino, Joseph P. 1999. Thirty years of change and stability. *Technological Forecasting and Social Change* 62: 13-18.

Moore, George E. 1965. Cramming more components onto integrated circuits. *Electronics* 38(8).

Neufeld, Jacob, George M. Watson Jr., and David Chenoweth. 1997. *Technology and the Air Force: A Retrospective Assessment.* Washington, D.C.: U.S. Government Printing Office, p. 41.

Porter, Alan L., Thomas A. Roper, Thomas W. Mason, Frederick A. Rossini, and Jerry Banks. 1991. *Forecasting and Management of Technology*. New York: John Wiley & Sons.

Rowe and Wright. 1999. The Delphi technique as a forecasting tool: Issues and analysis. *International Journal of Forecasting* 15(4): 353-375.

Stewart, Thomas R. 1987. The DELPHI technique and judgmental forecasting. *Climatic Change* 11: 97-113.

Strong, R., L. Proctor, J. Tang, and R. Zhou. 2007. Signpost generation in strategic technology forecasting. In *Proceedings of the 16th International Conference for the International Association of Management Technology (IAMOT)*, pp. 2312-2331.

Vanston, John H. 2003. Better forecasts, better plans, better results. *Research Technology Management* 46(1): 47-58.

Vanston, John H., and Lawrence K. Vanston. 2004. Testing the tea leaves: Evaluating the validity of forecasts. *Research Technology Management* 47(5): 33-39.

von Karman, Theodore. 1945. *Science*: *The Key to Air Supremacy*, summary vol., *Toward New Horizons: A Report to General of the Army* by H.H. Arnold, Submitted on behalf of the A.A.A. Scientific Advisory Group (Wright Field, Dayton, Ohio: Air Materiel Command Publications Branch, Intelligence, T-2). 15 December.

Wang, Clement, Xuanrui Liu, and Daoling Xu. 1999. Chaos theory in technology forecasting. Paper MC-07.4. Portland International Conference on the Management of Engineering and Technology. Portland, Oregon. July 25-29.

Wolfers, Justin, and Eric Zitzewitz. 2004. Prediction markets. National Bureau of Economic Research, Working paper W10504. Available at http://www.nber.org/papers/w10504. Last accessed October 28, 2008.

Copyright National Academy of Sciences. All rights reserved.

3

The Nature of Disruptive Technologies

To persistently and accurately predict disruption, forecasting system designers and operators must first understand the state of the global marketplace and the nature of disruption itself.

THE CHANGING GLOBAL LANDSCAPE

The global economy continues to be fueled by quickly flowing information, swiftly generated knowledge, and the myriad applications found for this information and knowledge. The new global economy is characterized by increased uncertainty, openness, flexibility, and choices, all of which impact lifestyle, business models, the working environment, the educational system, and national security.

The United States is the largest consumer in the world, as well as the largest exporter and importer, and accounts for more than one-quarter of global economic output. Yet, the U.S. economy cannot stand alone—it is an integral part of the global economy. Globalization in technology, jobs, and trade affects almost all sectors and industries both specifically and broadly. The creation of disruptive technologies is being affected by the globalization of information and trade, which in turn results in the globalization of jobs and affects the social environment.

On the global stage, increased production with less manpower and at lower cost is becoming the continual goal of all operations, making consistently increased productivity a relentless target. This goal stimulates profound changes in the structure and distribution of global and local job markets. For a given industrial function, the productivity bar has sharply risen, and fewer workers are required than a decade ago to perform an equivalent function. This productivity-driven environment intensifies outsourcing and offshoring, which have been evolving for many years even though only recently did their effects on jobs become more obvious.

During the half century after WWII, the transition from basic agriculture to advanced manufacturing drastically transformed some European and Asian countries, such as Korea, Taiwan, Singapore, and Ireland.

Another paradigm shift occurred more recently. The offshore operations of U.S. corporations, whose initial function was manufacturing, have changed to scientific research and technology development. During the 1970s and 1980s, Ireland and Singapore were the manufacturing centers of Europe and Asia, respectively. Today, they are redirecting larger portions of their workforce to pursue higher value activities such as scientific research, intellectual property creation, and system design and integration rather than supplying low-cost labor for assembly and manufacturing.

Further changing the global landscape is the increasing number of foreign students who come to the United

Copyright National Academy of Sciences. All rights reserved.

States to go to college but go back home after graduation to become important contributors to and leaders of their home workforce rather than to stay in the United States. Universities, research centers, and industries in the home countries of many such students are vastly improving. By the same token, the United States is losing its ability to attract top academic minds to its universities and research centers, and fewer foreign students have been coming to U.S. schools since September 11, 2001.

New and renewed issues in trade, laws (particularly those involving intellectual property), and politics, which impact the globalization of knowledge and jobs, continue to surface and be resolved. Asia's software, electronic, and microelectronic industries are clear illustrations of this. Countries in earlier stages of development are focusing on low-cost manufacturing, while those in the maturer stages are focusing on R&D and intellectual property creation. Over time, despite both gains and setbacks between the U.S. and Asian nations, U.S. and global demand for better information hardware, smarter software, and consumer electronics continues to grow, making Asia one of the most vibrant technology regions in the world.

As a result of the globalization and outsourcing that have occurred in recent years, several developments have been impacting industrial research and development:

- Global access to S&T knowledge, tools, resources, and capabilities,
- Shrinking R&D cycle,
- Faster product development in response to market demand,
- A shorter product development cycle due to global competition,
- A shortening product life cycle,
- Consolidation of the manufacturing sector,
- Globalization of production, and
- Global access to technology.

Technology and, more generally, knowledge are diffusing today at an unprecedented rate along pathways limited only by the global reach of the Internet. The S&T enterprise is now global, as has been observed by Thomas Friedman (2005) and others. This enables researchers who are far apart to rapidly build on the results of others, accelerating the advance in many areas. This new reality also increases the potential for disruption, since an advance made by one group of researchers can be exploited by another group working on a problem in an entirely different regime.

EFFECTS OF THE EDUCATION OF FUTURE GENERATIONS

Education is another aspect of the groundwork for disruptive technology to be considered. How will the priorities of S&T education affect the future workforce? How would a workforce educated in science and engineering exert disruptive effects decades later? At the time of this writing, petroleum-engineering graduates are becoming a hot commodity, commanding the top-paying engineering jobs and surpassing biomedical engineers popular during the 1990s (Gold, 2008). For 6 years (from 2001 to 2007) following the dot-com collapse, the U.S. college enrollment in computer science was significantly lower than in the 1990s and only began to make a comeback in 2008.[1] What long-term impact will these trends have?

ATTRIBUTES OF DISRUPTIVE TECHNOLOGIES

Researching the next big thing, also known as a "killer app(lication)," involves identifying innovations and their current and potential applications. To be disruptive, technologies need not be radical or novel from an engineering or technical point of view. Many become disruptive merely because they cross a tipping point in price or performance or dramatically increase accessibility and/or capabilities relative to the incumbent technologies. Sometimes, ubiquity also characterizes a disruptive technology.

[1]Available at http://www.nytimes.com/2009/03/17/science/17comp.html?_r=1. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

Two classes of disruptive technologies are generally observed. One displaces an incumbent technology in a phase transition, during which users adopt the new technology over a period of time. An early example of this was the transition from horse and buggy to the automobile. The latter revolutionized transportation and disrupted not only older transportation means but also several ancillary means. A more modern example of this is the transition from at-home movies from a VHS format to DVD, which saw a reversal in the ratio of DVD use from 9:1 to 1:9 in less than 5 years. The adoption of the DVD format, in conjunction with other events such as the rapid growth of broadband Internet technologies, has resulted in the distribution of digitized movies across the globe.

A second class of disruptive technologies creates a new market or capability where none had previously existed. The personal computer is an example of this class. Before the invention of the PC, computational resources were available only to large businesses, institutions, and governments. Most households did not have computers, and there was no perceived need for computation beyond that enabled by simple calculators. Today, personal computers are nearly as common a fixture in households as other appliances such as televisions, refrigerators, and telephones.

With history as a guide, several attributes seem to mark the birth of many disruptive technologies. First, there is a discontinuity when a key factor is plotted against time. The key factor could be performance, cost, reliability, adoption rate, or any of a number of characteristics that commonly describe a technology. The discontinuity may be related to a new application area and not to a change in the technology itself. Bringing an established technology into a new application can be disruptive within that application even when the technology itself is well worn.

Another attribute that should be considered when identifying disruptive technologies relates to their impact on other technologies. It is not sufficient for the application to be incidental; it needs to be impactful. Often overlooked in the history of the PC is the role played by the introduction of VisiCalc, the first important spreadsheet and data processing tool (see Figure 3-1).[2] It was this application of the PC, rather than its computational applications, that spurred its growth and interest in it. Indeed, before the introduction of VisiCalc, many sages of the day called PC technology a passing fad.

A third phenomenon attending the birth of many disruptive technologies is the convergence of more than a single discipline when a crossover technology is born. For example, the World Wide Web saw the coming together of computer, communications, and browser technologies.

A final and perhaps most important attribute relates to corporate vision. As Gerard Tellis points out, the quality of leadership within a sector is a strong force in promoting the introduction of a disruptive technology (Tellis, 2006). Leadership that emphasizes innovation, forward thinking, and a willingness to cater to an emerging rather than a historical (and often dominant) market will speed the introduction of a disruption that is any case inevitable. However, the disruption can occur only if it profits rather than threatens the corporation. Leadership is exemplified by Steve Jobs and his ability to transform Apple from a computer company to a technology lifestyle company (see Figure 3-2).[3]

From these observations, the committee concluded that a forecaster, when assessing the disruptive influence of a technology, may ask whether the technology does any of the following:

- Delivers a capability at a previously unavailable level, which may create disruptive forces;
- Combines with other technologies to create synergies, which may also be disruptive;
- Evolves from the nexus of seemingly unrelated technologies;
- Disrupts a workforce, society, or the economy when combined with multiple existing technologies;
- Generates products with new performance attributes that may not previously have been valued by existing end users;
- Requires users to significantly change their behavior to take advantage of it;
- Changes the usual product and technology paradigms to offer a competitive edge;
- Exponentially improves the value received by the user;

[2]Available at http://en.wikipedia.org/wiki/VisiCalc#cite_note-tomcalc-0. Last accessed October 29, 2008.
[3]A technology lifestyle company is a company that promotes the use of its technology to enhance day-to-day life.

Copyright National Academy of Sciences. All rights reserved.

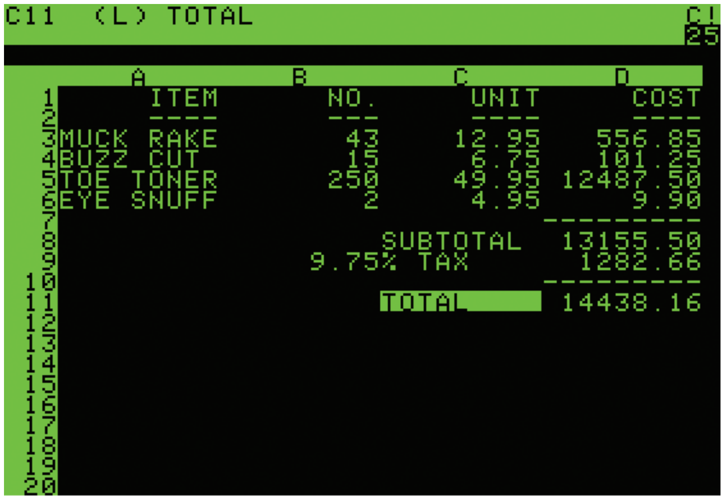


FIGURE 3-1 Screen shot of VisiCalc. SOURCE: Wikipedia. Used with permission from apple2history.org and Steven Weyhrich.

FIGURE 3-2 Steve Jobs presenting the iPhone. SOURCE: Courtesy of Wikimedia Commons. Used with permission from Blake Patterson.

Copyright National Academy of Sciences. All rights reserved.

- Creates industry growth through penetration or creates entirely new industries through the introduction of goods and services (if it is dramatically cheaper, better, and more convenient); or
- Becomes mainstream to a region, a country, or a community.

Categorizing Disruptive Technologies

When assessing whether a technology might be disruptive, it is useful to think about how it may disrupt. Disruptive technologies are impactful and affect other technologies. In many cases, it is not the technology that is disruptive but the way it combines with other factors or is applied. For example, the intercontinental ballistic missile (ICBM) combined a rocket motor, a nuclear warhead, and a guidance system. The guidance system was what made the ICBM effective and disruptive. The committee has identified six distinct categories of disruptive technology, to one of which every truly disruptive technology must belong:

- *Enablers.* Technology that makes possible one or more new technologies, processes, or applications—for example, the integrated circuit, the transistor, gene splicing, and cellular technology.
- *Catalysts*. Technology that alters the rate of change of a technical development or the rate of improvement of one or more technologies—for example, cloud computing and, in molecular biology, polymerase chain reaction (PCR) techniques for DNA sequence amplification.
- *Morphers.* Technology that when combined with another technology creates one or more new technologies—for example, wireless technologies and microprocessors.
- *Enhancers*. Technology that modifies existing technologies, allowing interest to cross a critical threshold—for example, existing technologies such as fuel cells, lithium ion batteries, nanotechnologies, and stealth technology.
- *Superseders.* Technology that obsoletes an existing technology, replacing it with a superior (better, faster, cheaper, or more capable) technology. Examples include the jet engine, LCD displays, and compact digital media.
- *Breakthroughs*. Discovery or technology that changes a fundamental understanding of nature or enables what had seemed impossible (if not improbable)—for example, quantum computing and fusion power.

Box 3-1 details one important technology disruption and the conditions that facilitated it.

Disrupter, Disrupted, and Survivorship

As a technology is deployed, there exists both the disrupter, who created or disseminated the disruptive technology, and the disrupted, who was voluntarily or involuntarily affected by this new technology. For example, when digital photography became popular with consumers, it was a devastating disruption to Kodak's chemical photo finishing and film business, forcing Kodak to develop an entirely new business model in order to survive in the digital age (Figure 3-3). Today, more camera phones are sold than cameras. Strategy Analytics forecasts that approximately one-third of the world's population will have a camera phone by 2011.[4] This may once again cause Kodak to shift its business model as the online posting of digital photographs replaces their printing.

Disruption also has a connotation of survivorship. A broad-based disruptive technology can lead to the destruction of an old technology, a business model or business vitality, a community, or a country's economy or security. For example, when online ordering became popular, it disrupted many conventional brick-and-mortar retail businesses as well as the way consumers shop. Successful disruptive technologies not only compete with, replace, and obsolete incumbent technologies but also can create completely new markets.

[4]Available at http://ce.tekrati.com/research/9039/. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

BOX 3-1
Qualitative Case Study: The Personal Computer

Although the microcomputer was invented in 1970, it wasn't until later in that decade that it became affordable and its form factor became acceptable for consumer and commercial applications. The advent of the personal computer (PC) and its subsequent applications exerted pervasive effects unnoticeable in the initial developing stage. These effects progressively and eventually caused disorder and habitual changes and have altered the status quo and the existing infrastructure. The PC changed the way we learn, communicate, do business, play, and live. Based on the level of impact and the nature of habitual interruption, it would be hard to argue that the PC was not a disruptive technology. Over the 1980s and 1990s, great strides in technological advancement, including the microprocessor, simultaneous multithreading (SMT) hardware assembling paired with software, and network technologies, evolved and revolutionized computing.

Four "game changers" allowed this transformation to take place—technology vanguards, "killer apps,"[a] open architecture, and the global economic conduit.[b] Commodore International, Tandy Corporation, and Apple Computer were the vanguards that introduced the PC to the market. Viscalc, the Microsoft Office suite, and the browser became the killer apps that turned PCs into critical productivity tools. The open architecture of IBM's corporate network and global reach made the PC ubiquitous.[c] Through the entrepreneurship of Taiwanese producers and the use of IBM's open architecture, the PC has become an affordable commodity in a relatively short period of time. Without these game changers, today's PC would either not have prevailed or would have taken a much longer time to penetrate the market to allow mass adoption.

The outcome of these events was stunning and the impact phenomenal. Today, it is difficult to imagine the world without personal computers; this is an example of a constructive disruptive technology being carried through the economic conduit and making a significant difference. Time and again, it has been shown that technology may need to undergo a series of innovations before reaching its disruptive potential. In such an environment, even a small enterprise can make a substantial difference to the market.

[a]Killer app: A highly desirable application that provides the core value of a technology.

[b]Global economic conduit: The ability to bridge one region's needs and another region's capabilities.

[c]Available at http://en.wikipedia.org/wiki/IBM_PC. Last accessed May 6, 2009. IBM also selected an open architecture, so that other manufacturers could produce and sell peripheral components and compatible software without purchasing licenses. IBM also sold an IBM PC technical reference manual, which included a listing of the ROM BIOS source code.

Life Cycle

A nascent technology[5] rarely becomes disruptive immediately. Each disruptive technology goes through an incubation period in six stages: (1) theoretical conception, (2) development of a proof-of-concept lab prototype, (3) attraction of funding for further development or technology maturation (this is the phase where many waver), (4) penetration into the niche markets of early adopters or limited application of the technology, (5) mass market acceptance or full-scale adoption, and (6) obsolescence, when it is finally disrupted by another technology or when the market vanishes.

Technology is dynamic. Technologies and their applications change, manufacturing efficiencies engender change, and the market demands change. Even serendipity leads to change. Today's successful disruptive technology becomes tomorrow's dominant technology, which in turn will eventually be subject to (perhaps disruptive)

[5]A nascent technology is a technology that requires entirely new structures and methods that have been demonstrated in a research environment but has not been refined enough for production (Wood and Brown, 1998).

Copyright National Academy of Sciences. All rights reserved.

FIGURE 3-3 A digital Kodak Easyshare system. SOURCE: Courtesy of Kodak.

replacement. Many factors affect the life cycle of a technology, including the cultural, economic, scientific, and engineering forces constantly at work in the marketplace.

The speed with which an emerging technology overtakes an established one also depends on many factors, which makes a quantitative assessment of the technology's life cycle extremely difficult. These factors include the potential market, applications, the economy, manufacturing ability, advertising, the competitive landscape, speed and veracity of adoption, improvements in performance, and cost. However, the new eventually becomes the old, and as an emerging technology becomes an established one, the cycle is likely to repeat itself.

The life cycle of a technology often forms an S-curve when performance is plotted against time. Because no technology is ever stagnant, such a characterization is an oversimplification. In fact, most technologies undergo a series of S-curves during their lifetimes, with a disruptive technology showing a discontinuity in this curve.

Timeline for Technology from Adoption Through Application

The timeline for a technology's adoption through its application does not need to be very short for the technology to be considered disruptive. There are many examples of disruptions that are not associated with rapid adoption and application.

The fundamentals of the Internet, developed in the 1960s, were built on the 1950s disruptive technology of packet switching. Packet switching was first used to create the Advanced Research Projects Agency Network, or ARPANET, built for the U.S. Department of Defense (DoD). However, it took almost three decades for the

Copyright National Academy of Sciences. All rights reserved.

Internet to be opened up for commercial use[6] and to reach broad deployment. Was the Internet disruptive? At its introduction, it was not considered to be inherently so. It took the introduction of the Web browser, a killer app, to turn the Internet into something that could be disruptive. While the microcomputer was invented in 1970, it was not until microcomputers were used in combination with productivity applications such as spreadsheets, word-processing software, e-mail, and the browser that they became sufficiently integrated into businesses and homes to be considered disruptive. The microcomputer made other goods, services, and equipment (such as typewriters) obsolete. It is interesting to observe that the productivity applications did not exert their impact until many years after their inception, showing that it may take time after deployment until a technology becomes noticeably disruptive.

While both emerging and disruptive technologies may have long adoption cycles, the latter experience massive discontinuity and nonlinearity in their adoption curves. Typically, they are rapidly adopted early on in vertical markets or across a specific demographic, and there can be a sizable timing gap between early adopters and mass adopters. Examples include the speed with which book readers adopted Amazon.com compared with general online consumers, and the speed with which college students adopted Facebook compared with the wider public.

Monitoring the Development of Potential Disruptions

Determining how to track key signposts is an important part of forecasting. A number of measurements can be monitored to anticipate the development of a disruptive technology or application; these are referred to as "measurements of interest." A forecasting system should track not only the rate of change of the parameters of interest but the second derivative of change—that is, the change in the rate of change. Accelerating rates of change may be an indicator of imminent disruption.

A signpost is a recognized and actionable potential future event. Some important signposts for signaling the emergence of a potentially disruptive technology are the following:

- The plateauing of any technology in terms of performance, cost, or efficiency;
- Emerging applications dependent on a single critical technology, especially those in a very competitive market, which may prompt the development of a disruptive alternate technology as a substitute;
- The production by incumbent producers of products and services that rely on sustaining innovations to improve existing technologies (faster, longer lasting, clearer, etc.) historically valued by customers (Christensen, 2004);
- Markets dominated by expensive products and services considered overpriced and too good relative to the needs of existing customers (Christensen, 2004); and
- Markets dominated by products that require deep expertise and/or significant wealth (Christensen, 2004).

ASSESSING DISRUPTIVE POTENTIAL

History reveals numerous technologies that never achieved their anticipated disruptive impact. Some failed because of barriers to adoption (e.g., pricing, use case, competition, or consumer acceptance); others failed because they turned out to be technologically or scientifically infeasible.

One example of a failure resulting from lack of adoption is the Segway, which was touted as a groundbreaking invention that would change personal mobility (Figure 3-4). While the Segway has made inroads in vertical applications like policing and security, consumers have not adopted it for everyday use. It seems that Segway was a solution looking for a problem: People viewed walking or riding a bike as healthier than riding a Segway.

An example of a technology that turned out to be infeasible was cold fusion. Immediately and widely publicized by the media, the scientific community later proved cold fusion to be unworkable.

[6]In 1992, Congress passed the Scientific and Advanced-Technology Act, 42 U.S.C. § 1862(g), permitting NSFNet to interconnect with commercial networks. OGC-00-33R Department of Commerce: Relationship with the Internet Corporation for Assigned Names and Numbers, Government Accountability Office, July 7, 2000, p. 6.

Copyright National Academy of Sciences. All rights reserved.

FIGURE 3-4 Field trials of the Segway by the police of Saarbrücken (Germany), February 2006. SOURCE: Courtesy of Wikipedia. Used with permission from Urban Mobility GmbH.

It is generally difficult to predict such failures be means of most forecasting approaches. However, if a forecaster pays attention to a broad range of opinion (including that of skeptics), it may be possible to distinguish technologies that will not meet expectations from those that are truly disruptive.

On the other hand, there are a number of conditions that facilitate innovation—in particular, technology disruption. These are described in the following sections.

Technology Push and Market Pull

The adoption of disruptive technologies can be viewed from two broad perspectives—technology push and solution (or market) pull (Flügge et al., 2006).

Technology Push

Technology push refers to disruption stemming from unanticipated technological breakthroughs in areas previously considered to have a relatively low probability of success. Such breakthroughs are most likely to occur when the basic science is not yet well understood (e.g., nanoscience) or where technological advancement is impeded by physical limitations (e.g., heat dissipation in semiconductor devices).

Technologies that are disruptive owing to technology push can come from very disparate areas of research, including biotechnology, cognitive technology, and materials technology. Particularly when they are combined with advances in nanotechnology and software, such sectors have the potential to create the building blocks for an extremely diverse range of applications.

Market Pull

The second perspective, solution (market) pull, refers to disruption attributable to market forces that result in the very rapid adoption of a technology (such as the exponential growth of Internet users after release of the World Wide Web) or stimulate innovative advances to address a significant need (such as currently emerging solutions for renewable energy).

When venture capitalists look for potentially disruptive technologies to invest in, they may search for markets that have threats, needs, or demands that could be addressed by novel technologies. They may also look for markets in desperate need of innovation and renewal, which could be threatened and disrupted through the

Copyright National Academy of Sciences. All rights reserved.

introduction of a new technology. Market need is a critical factor for determining a technology's potential value and market size. Some market pull conditions and their potential technological solutions follow:

- Reduce oil dependency: vehicles powered by alternative sources of energy.
- Reduce carbon emissions and slow global warming: green technologies.
- Protect vulnerable yet critical information networks: innovative cybersecurity technologies.
- Power portable devices: alternative portable power sources and battery technologies.
- Increase mobility: high-speed transportation networks.

When the Central Intelligence Agency (CIA) participated in the formation of In-Q-Tel, a 501c3 organization tasked with identifying and investing in new technologies and applications relevant to intelligence, its analysts drew up a set of critical needs they believed could be met through the use of innovative commercial technologies

In 2002, Secretary of Defense Donald Rumsfeld specified a capabilities-based requirements process for the Ballistic Missile Defense System (BMDS). BMDS was one of the first large-scale DoD programs that used a capabilities-based approach to acquisition instead of a requirements-based approach. Instead of specifying the method and performance requirements of a solution, the DoD described the capabilities necessary to overcome a generally defined projected problem or threat. Capabilities-based approaches call for the development of an initial capability and then spiral development to enhance the system as the problems and threats become more defined. Capabilities-based acquisition is fundamentally changing the way the DoD buys and engineers systems (Philipp and Philipp, 2004). This approach demonstrates that projecting future needs can be more important than specifying an exact technical solution.

The committee believes that same concept holds true for forecasting disruptive technologies. Forecasting future needs, problem areas, pain points, threats, and opportunities is just as important as forecasting the specific technologies that might cause disruptions. By associating market pull and capabilities with potential technologies, a forecast should be able to describe the disruption.

A good disruptive technology forecast should forecast not only potential technologies but also potential market (or military) opportunities, competitive threats, or problem areas that might drive technical innovation. Formulating a problem set and a capability list may let a decision maker know how to prioritize R&D initiatives and prepare for future disruptions. It may also help the decision maker take advantage of opportunities even if a pathway to the potential technical solution is not yet clear.

Investment Factors

When examining technology sectors from an investment perspective, it is important to distinguish between the fundamental research investments focused on technology push and investments in the development of new applications to address market pull. These two categories are not entirely decoupled, as most research is in fields that hold potential for application to known problems—for example, quantum science, nanoscience, and cognitive science—but the source of the funding and the kinds of applications being developed tend to be different.

Fundamental research, particularly in the United States, is primarily funded by the government and performed by academia. The results of this research are, in general, published openly (NRC, 2007). In fact, the U.S. export control regime contains an explicit exemption pertaining to the results of fundamental research. Investment in fundamental research in other nations can be less transparent than in the United States. There is a growing trend to funding international collaborations among academic researchers, particularly in the basic research for nanotechnology, biotechnology, information technology, and cognitive science. Because of concerns about intellectual property protection and global competitiveness, the many research programs sponsored by large, multinational corporations are kept confidential and their results are proprietary.

Venture capital is a significant and growing source of investment for technological innovation intended to address market demand and promote regional S&T objectives. Of the $11 billion invested in fuel cell development in the United States between 1997 and 2009, $1 billion came from venture capitalists (Wu, 2009). This type of funding is particularly important for small corporations and start-ups, although some large corporations have

Copyright National Academy of Sciences. All rights reserved.

implemented an internal version of venture capital investment to focus on the need to link investment and market demand. It is possible to monitor investment trends by sector (cleantech,[7] biotechnology, Web, enterprise, and consumer electronics) as well as region or country. Information on venture capital can be found in the publications of venture capital associations as well as from analytical groups that track and report on venture investing. Nevertheless, it remains difficult to identify funding activities by specific application, given the proprietary nature of many start-ups.

A slightly different perspective on investment can be obtained by analyzing corporate acquisitions. Large corporations in particular often buy a smaller corporation to gain access to new technology that they then exploit in existing or new product lines.

It is worth noting that the size and type of the investment required to foster technological advancement vary significantly by sector. For example, software development requires virtually no investment in infrastructure beyond basic computing capabilities, whereas nanotechnology development requires significant laboratory capabilities (NRC, 2008). Similarly, the emerging field of computational biology relies on computing power, whereas biotechnology more generally requires significant investment in laboratory equipment.

Cost as a Barrier to Disruption

Cost can be measured in multiple dimensions. First, there are costs related to human capital. Although the science and technology enterprise is increasingly global, the expertise is not uniformly distributed. Next, there are costs related to the infrastructure required to enable research and development; this ranges from basic computing capabilities to sophisticated laboratory equipment and testing facilities. Finally, there are costs relating to the replication of a product once it is developed. These costs may be virtually nonexistent if the product is software (particularly open source) but can increase significantly depending on the complexity of the end product. The F-22 Raptor is one good example of an extremely complex product with high replication costs.

Another perspective on the implementation cost relates to political and cultural barriers that can impede dissemination. Such impediments may be the result of the national policy or regulatory environment or, more broadly, international conventions or norms. Because global policies and norms vary so widely, a technology that is acceptable in most places may not be acceptable in the United States and could have a disruptive impact. Such variation may foster or constrain the conduct of specific research as well as its subsequent application. Examples include research on stem cells and cloning. Similarly, local conditions may create massive market pull and disproportionately high rates of adoption, luring investment and stimulating innovation by corporations addressing the global marketplace. Pagers, for example, were adopted much more rapidly in China than in United States. In short, geography matters. Any methodology for forecasting disruptive technologies must consider regional and national perspectives and account for international influences.

It is relevant to note that it is not always the innovator who is rewarded when a disruptive application emerges. In the era of instant communication and connectivity, imitation can replace innovation as time goes on. A conscientious and astute imitator can give birth to disruption with perhaps even greater ease than can the innovator, since the imitator can search the entire technology spectrum with little or no vested interest, capital, commitment, or sentimental attachment to any specific pathway.

Regional Needs and Influences

The continuing globalization of the science and technology enterprise, as well as the commercial marketplace it supports, further complicates the ability to forecast disruptive technologies. The “flat world” accelerates the pace of innovation as researchers in one region of the world build on the work of researchers elsewhere. However, this borderless flow of knowledge may not translate into the global uniformity of a technology or its applications,

[7] “Cleantech” is used to describe knowledge-based products or services that improve operational performance, productivity, or efficiency while reducing costs, inputs, energy consumption, waste, or pollution. Available at http://en.wikipedia.org/wiki/Cleantech. Accessed on August 11, 2009.

Copyright National Academy of Sciences. All rights reserved.

which may vary between regions because each nation responds to regional needs and global opportunities in different ways. Such effects may be amplified when individual nations make sizeable strategic investments, targeting research to address specific national priorities and stimulating advances with global impact.

The regional or national potential for disruptive technologies can be assessed on several dimensions, including stability (does the region have the requisite institutions to sustain innovation?), velocity (are new industries or technology sectors emerging?), diversity (do the technology sectors in a given cluster have substantial diversity?), and need (is there a critical or strategic need for a technological solution?). The richness of connections, both physical and electronic, between regions and countries is also a crucial factor.

The variation in national policies, mentioned above, also affects national attitudes to developing, handling, and deploying military and intelligence-related technologies. Variations are found in nuclear (tactical and strategic), chemical, biological, mining, stealth, missile defense, space, and cyber technology research policies. Some of them are driven by strategic needs, ethics, or cultural concerns, while others are driven by accessibility, cost, and scientific, technical, and engineering capabilities.

Infrastructure capacity also varies significantly by nation. During the 1990s, India became a significant source of software development (Arora et al., 2000). This was leveraged in large measure by Silicon Valley and U.S. corporations, which recognized that while software development required a skilled and educated workforce; it did not need much physical infrastructure. However, while the number of nations able to support sophisticated laboratories for advanced research in, say, biotechnology, nanotechnology, quantum technology, and high-energy research is growing, they are limited by the quality of the infrastructure and the availability of financial and human resources.

Social Factors

Social and cultural attitudes have always played a role in the viability and impact of technology and its applications. In many cases, social and cultural attitudes are as important for technology disruption as are performance and functionality factors.

Many technologies and applications are adopted not only for what they do (functionality) but also for what they mean (social identity).[8] One driver of technology adoption is identity reinforcement. The following examples of social identity affect the adoption of technologies and their applications:

- Being green (e.g., buying an electric or hybrid car);
- Displaying affluence (e.g., driving a very expensive sports car);
- Demonstrating computer savvy (through choice of computer operating system);
- Having a high-tech lifestyle (e.g., using smart phones and digital media players);
- Being connected (such as by posting on social networking sites); and
- Being a superpower (e.g., by possessing or aiming to possess nuclear weapons).

Technologies and applications may also be resisted for cultural, religious, or ethical reasons that make certain technologies unacceptable. Examples include the banning in various cultures of cloning, human genetic modification, embryonic stem cell technologies, contraceptives, and government surveillance of a person's activities through electronic data using data-mining technologies. Regional preferences also affect the social acceptability of a technology or resistance to it. Examples include the resistance to nuclear power in the United States, to bioengineered foods in Europe, and to nuclear weapons in Japan.

Demographic Factors

Generally, younger adults are much more prone than older adults to take risks. These risks can include sensation seeking (for example, thrill seeking and a predilection for adventurous, risky, and exciting activities), experience seeking (such as a desire to adopt a nonconforming lifestyle), disinhibition (a need for social stimulation), and susceptibility

[8]Available at http://www.kk.org/thetechnium/archives/2009/03/ethnic_technolo.php Last accessed July 13, 2009.

Copyright National Academy of Sciences. All rights reserved.

to boredom (avoidance of monotonous situations) (Zuckerman, 1979; Trimpop et al., 1984). Indeed, recent research has shown that the age-associated differences in acceptability of risk have a neuropsychological basis. For example, Lee and colleagues found that younger and older adults relied on different brain mechanisms when they were making decisions about risk (2008). This research suggests that neuropsychological mechanisms may underlie decisions on risk and cause impulsive behavior across an individual's life span. In keeping with this effect, younger researchers, scientists, and entrepreneurs may be more willing to risk their careers and financial well-being to pursue the research, development, and application of risky but potentially disruptive, highly profitable innovations.

Owing in large measure to the ongoing globalization of the S&T enterprise, it is increasingly difficult to map human expertise around the world with any degree of fidelity. Trends of college graduates in various disciplines around the world provide an indirect indication. New research facilities under construction by corporations may also be indicative, as they are motivated to locate near pools of talent. Demographic trends, particularly in population growth, can be a determinant of human potential, which is maximized in countries emphasizing technical education.

In examining geographic and demographic factors, it is therefore important to consider not only a nation's wealth but also its population trends and emphasis on education. It also is instructive to assess that nation's commitment to S&T. A number of nations plan to invest a growing percentage of their gross domestic product in scientific research, a promising indicator for future technological innovation.

Geopolitical and Cultural Influences

This area of analysis includes not only the geopolitical and cultural influences that may extend beyond the boundaries of a given nation, but also the social influences stemming from a demographic that is globally impacted by technology-savvy youth. Each of these dimensions may serve to impede, or accelerate, the development and diffusion of a given technology.

Historically, there has been concern for disruption stemming from geopolitical influences in areas where transparency is minimal due to an intentional disregard for international conventions or norms. For example, although many nations have accepted limitations on the use of biological and chemical weapons for warfare, there is no guarantee that the United States will not encounter such weapons on future battlefields. Other asymmetric techniques made possible by emerging technologies may fall into this category as well.

Differing cultural beliefs, on the other hand, may be quite transparent and nonetheless lead to some degree of disruption simply by virtue of the creation of capabilities that would not be anticipated in certain cultural environments. Human cloning or more general human enhancements would fall into this category.

Overall, the strengths of each country or region in specific scientific research areas vary. Technology priorities may also vary by country or region depending on societal needs and governmental policies. So, uniformity cannot be expected.

Practical Knowledge and Entrepreneurship

For researchers in the academic, commercial, and government sectors, two factors are production-worthiness and market fit. Academic researchers need not only master scientific and engineering expertise, but must also embrace market tastes, needs, and demands. To swiftly move scientific knowledge and discoveries from the laboratory to the development and manufacturing stages and, finally, to the marketplace, practical knowledge and entrepreneurial agility are required. Entrepreneurship is a key ability for the workforces of fast-growing countries, enabling them to move expeditiously from science to technology to commercialization.

Crossover Potential

The potential for surprise is greatest in crossover advances, which are the most difficult to anticipate. In the area of pharmaceuticals, for example, there are instances where a drug designed for therapeutic purposes is used instead for the enhancement of physical capabilities—for example, the use of steroids by athletes (see Figure 3-5).

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

FIGURE 3-5 Steroid product for athletes. SOURCE: Reprinted with permission from Custom Medical Stock Photo.

Another example is the Internet, which was originally envisioned as a means for researchers to communicate with one another and to share the computational resources of powerful research computers no matter where they were.[9] The Internet subsequently became a global backbone for communications and now supports a diverse array of applications for which it was never designed. One of the "applications" supported by the Internet is the delivery of cyberattacks, which have significant disruptive potential. Thus, to assess this potential for a given technology sector or application, forecasters must ask "What else?"

CONCLUSION

This chapter has overviewed the general features of disruptive technologies that must be considered, such as the attributes, categories, and timelines associated with these technologies. The timeline of a technology's deployment does not necessarily need to be very short for the technology to be considered disruptive, and its cycle can vary, with most technologies undergoing a series of S-curves of growth and development during their lifetimes. Approaches to assessing the likelihood of a given technology disruption were also discussed, including the impact of geographic, demographic, cultural, and social factors. Signposts (metrics that can be used to anticipate the development of a disruptive technology) were emphasized.

Chapters 4 and 5 specifically address the characteristics of a forecasting system for disruptive technologies, including how bias can affect a forecast and the necessary attributes of such a system.

[9]Available at http://inventors.about.com/library/inventors/bl_Charles_Herzfeld.htm. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

REFERENCES

Arora, Ashish, V.S. Arunachalam, Jai Asundi, and Ronald Fernandes. 2000. The Indian software services industry. *Research Policy* 30(8): 1267-1287.

Christensen, Clayton. 2004. *Seeing What's Next: Using the Theories of Innovation to Predict Industry Change.* Watertown, Mass.: Harvard Business School Publishing Corporation.

Flügge, Barbara, Till Janner, and Christoph Schroth. 2006. Technology push vs. market pull. Second European Conference on Management of Technology. Birmingham, England. September 10-12. Available at http://www.abs.aston.ac.uk/newweb/research/documents/EuroMOTkeynotepresentationFluegge.pdf. Last accessed November 12, 2008.

Friedman, Thomas L. 2005. *The World Is Flat*. New York: Farrar, Straus and Giroux.

Gold, Russell. 2008. A gusher for oil grads. *The Wall Street Journal*. February 21.

Lee, Tatia M.C., Ada W.S. Lueng, Peter T. Fox, Jia-Hong Gao, and Chetwyn C.H. Chan. 2008. Age-related differences in neural activities during risk taking as revealed by functional MRI. *Social Cognitive and Affective Neuroscience* 3(1): 7-15.

National Research Council (NRC). 2007. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. Washington, D.C.: The National Academies Press. Available at www.nap.edu/openbook.php?isbn=0309100399.

NRC. 2008. *Nanophotonics: Accessibility and Applicability*. Washington, D.C.: The National Academies Press. Available at http://www.nap.edu/catalog.php?record_id=11907#toc.

Philipp, Charles, and Turner Philipp. 2004. Capabilities based acquisition . . . from theory to reality. *CHIPS - The Department of the Navy Information Technology Magazine.* Summer.

Tellis, Gerard J. 2006. Disruptive technology or visionary leadership? *Journal of Product Innovation Management* 23(1): 34-38.

Trimpop, Rudiger M., John H. Kerr, and Bruce Kirkcaldy. 1984. Comparing personality constructs of risk-taking behavior. *Personality and Individual Differences* 26(2): 237-254.

Wood, S., and G. Brown. 1998. Commercializing nascent technology: The case of laser diodes at Sony. *The Journal of Product Innovation Management* 15(2): 167-183.

Wu, Ying. 2009. *Finding Fuel Cells' Real Future.* Available at http://www.luxresearchinc.com/. Last accessed June 3, 2009.

Zuckerman, Marvin. 1979. *Sensation Seeking: Beyond the Optimal Level of Arousal*. Hillsdale, N.J.: Erlbaum.

Copyright National Academy of Sciences. All rights reserved.

4

Reducing Forecasting Ignorance and Bias

INTRODUCTION

When imagining an ideal disruptive technology forecasting system, the potential negative impacts of individual bias and forecasting bias on forecasts were a key consideration of the committee.[1] While no data source can be assumed to be free of biases, balancing sources of information can help to reduce overall forecasting bias. For example, forecasters who rely primarily or exclusively on Western experts and data sources are at a higher risk of producing an unbalanced and biased forecast. Such forecasts can create planning blind spots resulting from cultural mirroring[2] and false assumptions. A biased forecast gives an incomplete view of potential futures and increases the probability that the user will be unprepared for a future disruptive act or event.

A 1992 article by Faber and colleagues introduced "ignorance," or a lack of information, as another source of surprise in addition to the traditional economic concepts of risk and uncertainty (Faber et al., 1992a). Based on Faber's article, the committee chose to distinguish these three terms in the following way:

- *Risk*. Occurs when the probabilities of outcomes are thought to be known;
- *Uncertainty*. Occurs when the outcomes are known (or predicted) but the probabilities are not; and
- *Ignorance*. Occurs when the outcomes are not known (or predicted).

IGNORANCE

Ignorance is a significant source of forecasting bias, which in turn causes forecasting failures and disruptive surprises. According to Faber et al., ignorance can be categorized as either closed or open, and both types can be a key source of surprise (Faber et al., 1992a). Closed ignorance occurs when key stakeholders are either unwilling or unable to consider or recognize that some outcomes are unknown. In this case, the stakeholders have no knowledge of their own ignorance. Conversely, open ignorance occurs when the key stakeholders know what it is that they don't know.

[1]For purposes of this report, the committee defines "individual bias" as a prejudice held by a person and "forecasting bias" as incompleteness in the data sets or methodologies used in a forecasting system.

[2]Cultural mirroring, also known as mirror imaging, is the assumption that one's beliefs and values are held by everyone else.

Copyright National Academy of Sciences. All rights reserved.

Closed Ignorance

Closed ignorance can affect individuals and organizations alike. One form of closed ignorance stems from individuals and groups that are averse to recognizing possible disruptions as they pursue their goals or objectives. This ignorance can be partially countered by opening the system to outside opinion. Gerard Tellis, with the University of Southern California, has conducted several studies involving disruption and market incumbents. Tellis (2006) argues that

> the disruption of incumbents—if and when it occurs—is due not to technological innovation per se but rather to incumbents' lack of vision of the mass market and an unwillingness to [redirect] assets to serve that market.

Faber and colleagues suggested that closed ignorance occurs due to "false knowledge or false judgments" (Faber et al., 1992b). False truths may result from the overreliance on an inadequate number of perspectives or observations. Key decision makers of the persistent forecasting system should be made aware of closed ignorance at the outset and put in place a set of processes to mitigate this form of bias. Further, these bias mitigation processes should be evaluated on a periodic basis by both a self-audit and a third-party assessment. The composition of the decision-making group should be included in this review process.

One method of overcoming forecasting bias due to closed ignorance is to increase the diversity of the participants in the forecast. This can be accomplished by creating and implementing a Web-based forecasting system designed for global participation. Another approach is to incorporate forecasting activities such as workshops, surveys, and studies from other countries. The more diverse the participants, the more likely it is that all perspectives, including many of the outliers, will be captured.

Open Ignorance

Open ignorance assumes that key stakeholders of the persistent forecasting system are willing to admit to what they don't know. Costanza and colleagues build on Faber's work to suggest that there are four main sources of surprise that result from open ignorance (Costanza et al., 1992):

- Personal ignorance,
- Communal ignorance,
- Novelty ignorance, and
- Complexity ignorance.

Personal Ignorance

Personal ignorance results from lack of knowledge or awareness on the part of an individual. The impact of personal bias on a forecast can be mitigated by incorporating multiple perspectives during both data gathering and data analysis—that is, at every stage of the persistent forecasting system process, including during idea generation, monitoring and assessment, escalation, and review. Converging these multiple perspectives could be dangerous, however, owing to the tendency to develop a consensus view instead of a diversity of views. Gaining an understanding of a more diverse set of viewpoints helps reduce personal ignorance.

According to Karan Sharma of the Artificial Intelligence Center at the University of Georgia, "each concept must be represented from the perspective of other concepts in the knowledge base. A concept should have representation from the perspective of multiple other concepts" (Sharma, 2008, p. 426). Sharma also cites a number of studies that discuss the role of multiple perspectives in human and machine processes (Sharma, 2008).

The concept of multiple perspectives is also embedded in many of the forecasting and analytical processes discussed elsewhere in this report or is a guiding principle for them, including scenario planning, stakeholder analysis, and morphological analysis. When groups such as a workshop are assembled for gathering or interpreting data, system operators should strive to create set of participants that is diverse in the following characteristics:

Copyright National Academy of Sciences. All rights reserved.

age, wealth, education, career path, scientific specialization, culture, religion, countries, languages, economic philosophy, and political perspective.

Communal Ignorance

A technology may not be immediately recognized by a group or community as disruptive for a number of reasons, including an early judgement that it is not likely to be successful, an initially slow rate of adoption, or a lack of imagination. Numerous academic papers propose lack of imagination as the primary reason for disruption. To various degrees, lack of imagination contributes to most forms of bias or ignorance but appears to be particularly acute in groups or communities who by definition may assemble because of similar viewpoints and who may accordingly be less willing to consider others' views. For the same reason, ignorance may also be due to lack of knowledge. According to Faber and colleagues, another cause of communal ignorance is that "there is no information available to society concerning this event. By research, however, it would be possible to obtain this information" (Faber et al., 1992b, p. 85). According to the Aspen Global Change Institute's *Elements of Change* report, communal ignorance can be overcome through the acquisition of new knowledge achieved "through research, broadly within existing scientific concepts, ideas, and disciplines" (Schneider and Turner, 1995, p. 8).

Many forecasts are generated by a relatively small group of similar individuals (e.g., of the same age group, educational background, culture, or native language). A persistent forecasting system should reduce communal ignorance by including a broader set of communities and viewpoints, such as an open system that encourages global participation. With the advent of the Internet, it is now easy to create Web-based systems that allow individuals anywhere to collaborate on virtually any topic at any time. By leveraging communities of interest and public domain sources of information, open collaboration systems may be used to envision a broader range of possible disruptions.

The persistent forecasting system should utilize processes such as scenario methods and gaming to "imagine the unimaginable" and develop multiple views of potential futures in areas identified as key priorities. Importantly, these techniques must encourage and capture fringe or extreme thoughts from individuals who might be expected to come up with early signals of potential disruptions.

When participation from individuals or groups representing certain viewpoints is insufficient, system designers will need to find ways to encourage greater participation. If the sources of such viewpoints are not available or accessible, proxies may need to be created to replicate the viewpoints. Red teaming and adversary simulations are time-tested methods of creating proxies.

Novelty Ignorance

Jesus Ramos-Martin suggests that novelty ignorance can stem from the inability to anticipate and prepare for external factors (shocks) or internal factors such as "changes in preferences, technologies, or institutions" (Ramos-Martin, 2003, p. 7). Natural disasters and resource crises such as limited water, energy, or food are examples of external shocks that might cause novelty ignorance.

While it is difficult, if not impossible, to forecast the exact timing of external shocks, decision makers can benefit from the simulation and gaming of alternative futures to gain better insight into the impact of various shocks under different scenarios. These insights can be used to mitigate the impact of surprise by encouraging the allocation of resources before the surprise occurs.

Complexity Ignorance

Surprise may also be caused when information is available but insufficient tools are available to analyze the data. Thus, interrelationships, hidden dependencies, feedback loops, and other factors that impact system stability may remain hidden. This special type of challenge is called complexity ignorance.

Our world is comprised of many complex adaptive systems (CASs), such as those found in nature, financial markets, and society at large. While personal and communal ignorance can be mitigated, ignorance coming from

Copyright National Academy of Sciences. All rights reserved.

a failure to understand or model complex systems is more difficult to deal with. It is therefore worthwhile to examine complexity ignorance in more detail. According to John Holland, a member of the Center for the Study of Complex Systems at the University of Michigan, a CAS is

> a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents. (Waldrop, 1992)[3]

Also, Kevin Dooley (1996) elaborates further:

> A CAS behaves/evolves according to three key principles: (i) order is emergent as opposed to pre-determined; (ii) the system's history is irreversible;[4] and (iii) the system's future is often unpredictable.[5]

The University of Michigan's Center for the Study of Complex Systems describes CASs as follows:

> In a complex system the agents are usually numerous, diverse and dynamic. They are intelligent but not perfect decision makers. They learn and adapt in response to feedback from their activities. They interact in structured ways, often forming organizations to carry out their tasks. They operate in a dynamic world that is rarely in equilibrium and often in chaos.[6]

Many of the systems we live in—natural, financial, and social—can be defined as CAS. Complexity ignorance arises because the world currently lacks, and may never have, the computational tools necessary to precisely model the behavior of all of the individual agents and forces or the behavior of the system as a whole. Further, complexity theory suggests that the agents do not always act rationally. Even if the agents were to act rationally, the system itself might show irrational behavior. Finally, it is extraordinarily difficult to determine cause and effect, or secondary and tertiary level interrelationships and dependencies. While the committee recognizes the inability to precisely model complexity, it does believe that at a minimum several major complex systems should be tracked in order to discover changes in macro effects. There are an increasing number of tools available that can be used to deepen our understanding of complex systems and garner early warnings of potential forces of disruption.

Summary of Ignorance Mitigation Methods

Table 4-1 summarizes the forms of ignorance and the committee's suggested methods for mitigation.

BIAS

No matter whether one is assembling groups of people for data gathering (through workshops, scenarios, games, etc.) or collecting data from other sources, it is critical that system operators understand the main sources of individual and forecasting bias. Because ignorance is a key cause of both forecasting and individual bias, the recommended methods for reducing ignorance are essential tools for bias mitigation. The preceding section dealt with methods to mitigate human ignorance and surprise. This section identifies several potential sources of bias and discusses their impact on a forecast.

A key question to ask is which individual, group, or region would benefit most or be hurt most by the disruptive technologies being forecasted. To have a comprehensive system that is able to identify potential disruptions

[3]Available at http://en.wikipedia.org/wiki/Complex_adaptive_system. Last accessed October 23, 2008.
[4]In Wolfram's A New Kind of Science, this concept is also known as computational irreducibility (2002).
[5]Available at http://en.wikipedia.org/wiki/Complex_adaptive_system. Last accessed November 19, 2009.
[6]Available at http://www.cscs.umich.edu/about/complexity.html. Last accessed October 23, 2008.

Copyright National Academy of Sciences. All rights reserved.

TABLE 4-1 Forms of Ignorance and Methods of Mitigation

Ignorance	Description	Methods of Mitigation
Closed ignorance	Information is available but forecasters are unwilling or unable to consider that some outcomes are unknown to the forecaster.[a]	Self-audit process, regular third-party audits, and open and transparent system with global participation
Open ignorance	Information is available and forecasters are willing to recognize and consider that some outcomes are unknown.	
Personal	Surprise occurs because an individual forecaster lacks knowledge or awareness of the available information.	Explore multiple perspectives from a diverse set of individuals and data sources for data gathering and analysis
Communal	Surprise occurs because a group of forecasters has only similar viewpoints represented or may be less willing to consider the views of forecasters outside the community.	An open and transparent platform that includes viewpoints, data, and assets from a broader set of communities; "vision-widening" exercises such as gaming, scenarios, and workshops; creation of proxies representing extreme perspectives
Novelty	Surprise occurs because the forecasters are unable to anticipate and prepare for external shocks or internal changes in preferences, technologies, or institutions.	Simulating impacts and gaming alternative future outcomes of various potential shocks under different conditions
Complexity	Surprise occurs when inadequate forecasting tools are used to analyze the available data, resulting in inter-relationships, hidden dependencies, feedback loops, and other negative factors that lead to inadequate or incomplete understanding of the data.	Track changes and interrelationships of various systems (i.e., nature, financial markets, social trends) to discover potential macro-effect force changes

[a]Outcomes that are unknown are sometimes described as outcomes that are unpredictable in principle. One never could envisage them a priori because one cannot make even tentative predictions about the likely range of all possible outcomes. Philip Lawn, *Toward Sustainable Development* (Boca Raton, Fla.: CRC Press, 2000), p. 169.

from all parts of the globe, it is essential that a wide range of cultures, industries, organizations, and individuals contribute to the data collection efforts. Forecasting bias occurs when a forecast relies too heavily on one perspective during data-gathering, data analysis, or forecast generation.

A broad assessment of the demographics of potential participants and data sources must be a critical design point of the persistent forecasting system. This assessment can be accomplished through appropriately designed questionnaires, interviews, and surveys of the participants as well as analysis of the sources of the data being used in the forecast. The goal of such an exercise is to achieve balance in a forecast.

To reduce bias, the system should encourage participants to be open about personal characteristics that could help identify potential biases. Special attention needs to be given to age and culture diversity.

Age Bias

One common individual bias is the assumption that future generations' acceptance of new technologies will mirror that of today's users. Examples include the rejection of virtual presence in favor of physical presence for social interaction, the preference for paper books to electronic books, and trust of expert-sourced rather than crowd-sourced information. Technologies that are not accepted by today's user may be easily accepted by users 10-20 years from now.

When applied to forecasting, age bias can be counteracted by gathering sufficient input from the generations of scientists, entrepreneurs, and technologists who will most likely create the future disruptive technologies and

Copyright National Academy of Sciences. All rights reserved.

applications. According to Dean Simonton, the age of outstanding achievements for an individual appears to be highly contingent on the discipline, with peaks in the early 30s for fields such as lyric poetry, pure mathematics, and theoretical physics and in the later 40s and 50s for domains such as the writing of novels, history, philosophy, medicine, and general scholarship (Simonton, 1988).

Another individual age-related bias is the assumption that one generation's view of the future will be the same as another generation's. Research suggests that younger people are more future-oriented than older people (Carstensen et al., 1999; Fingerman and Perlmutter, 1995), maybe because the former may perceive time as expansive or unlimited and tend to be more future-oriented. They are motivated to acquire new knowledge about the social and physical world and to seek out novelty (for example, meeting new friends or expanding their social networks). They also tend to be more concerned about future possibilities. Conversely, older people may perceive time as limited and tend to be more focused on the present. It has been suggested that this leads them to have a smaller number of meaningful relationships, to work to sustain positive feelings, and to be less motivated to acquire new knowledge. In other words, they may be more concerned about savoring the present than about changing the future. Forecasting bias can occur in systems that are not sufficiently future- or youth-oriented.

Mitigating Age Bias

One approach to mitigating age bias is to consider the time horizon of the forecast and then seek out participation from projected users and creators of disruptive technologies. For example, if pioneers in medicine are typically in their 40s and 50s, it would be appropriate to seek input from postdoctoral researchers in their 30s when developing a 20-year disruptive technology forecast. A common mistake is to survey opinions of the future only from older and well-established experts in the field.

Another approach is to consider the technological environment that surrounds youth today to gain a better understanding of the acceptability of future technologies. For example, How will future generations of warfighters feel about the use of robots and drones as the principal form of warfare? While many of today's warfighters might reject the notion of automated warfare, future warfighters (today's youth) who are growing up with video games, the Internet, robotic toys, mobile smart devices, virtual presence, and social networks may have a completely different attitude.

Cultural Bias

The committee believes that cultural factors should be considered when assessing the quality of a data source or when analyzing the data. There is ample quantitative data showing that societies around the globe vary considerably in their values, beliefs, norms, and worldviews (Bond et al., 2004; Gelfand et al., 2007; Hofstede et al., 1990; House et al., 2004; Schwartz, 1994). Research has yielded metrics for the dimensions in which cultures vary. At the cultural level, these dimensions often reflect basic issues surrounding the regulation of human activity that all societies must confront—issues that are solved in different ways (Schwartz, 1994). Such variability must be taken into account when identifying potential disruptive technologies for a number of reasons:

- They can affect what is seen as disruptive.
- Special incentives may be required to motivate individuals to discuss potential disruptive technologies.
- Individuals from diverse cultures may feel more or less comfortable about communicating potential disruptions depending on the means of data gathering.

Because cultures vary widely with respect to their values, beliefs, worldviews, resources, motivations, and capabilities, the sampling must be as wide as possible. Within and across societies, it is essential to capture variation in age, socioeconomic status, gender, religion, population density, experience, and industry. Disruptive technologies can occur anywhere at any time and for any demographics. Accordingly, the system must collect wide and diverse data, be capable of supporting multiple languages, provide adequate and appropriate incentives, and employ multiple methodologies.

Copyright National Academy of Sciences. All rights reserved.

It is worth noting the counterargument to this—namely, that globalization is making the world more homogeneous, obviating the need for concern about cultural differences. Already, skeptics argue that youth in many countries—from the United States to Japan to Zimbabwe—are all eating Big Macs, drinking Coca-Cola, and wearing Levi's, causing a homogenization of world culture. As noted by Huntington, this argument is missing the essence of culture, which includes at the most basic level deeply rooted assumptions, beliefs, and values (Huntington, 1996; Triandis, 1972). Huntington also notes that "non-Western societies can modernize and have modernized without abandoning their own cultures and adopting wholesale Western values, institutions, and practices" (Huntington, 1996, p. 78). Some even argue that cultural identity is on the rise with the end of the superpower divide and the consequent emergence of age-old animosities (Huntington, 1996). Moreover, cross-cultural conflicts are pervasive throughout the world, and the anger and shame that result from these conflicts can even instigate development of disruptive technologies. Culturally distinct contexts therefore are important to recognize and assess. In all, the argument that cultural differences are no longer important (or will cease to be important) in the study of disruptive technologies is not tenable.

Mitigating Cultural Bias

Because cultural differences have been demonstrated to have a pervasive effect on human cognition, motivation, emotion, and behavior (Gelfand et al., 2007), their implications for an open, persistent forecasting system must be assessed and minimized.

First, as previously noted, the concept of a disruptive technology is complex, and adding a cultural facet to its definition makes it even more so. It must be remembered that cultural differences can affect not only the approach to developing a broad and inclusive system but can also change what is perceived as disruptive.

Second, different incentives may be needed to motivate participants from different cultures during the information-gathering process. For example, monetary incentives offered by strangers might be suitable in highly individualistic cultures (such as the United States, Australia, and many countries throughout Western Europe). However, even in these countries, where out-groups may be distrusted, it may be necessary to go through trusted social networks. For this reason, it is critical to develop networks of local collaborators around the globe to facilitate the information-gathering process.

Third, cultural differences in familiarity and comfort with the methodologies used to extract information may also bias the results. Cross-cultural psychology can document numerous problems with gathering data that can affect the reliability and validity of the data collected (Gelfand et al., 2002; Triandis, 1983). Not all methodologies yield equivalent results across cultures; they will vary in the extent to which they are familiar, ethnically appropriate, reliable, and valid. Without taking these issues into account, the data and conclusions will be culturally biased.

Reducing Linguistic Bias

The language in which information is gathered can also bias the responses. For example, responses from Chinese study participants in Hong Kong differed widely depending on whether instructions were given in Mandarin, Cantonese, or English (Bond and Cheung, 1984). The authors of that study proposed that the respondents varied their answers according to who they thought was interested in the results—the Beijing authorities, the Hong Kong authorities, or the British authorities. Bennett, too (1977), found that bilingual persons gave more extreme answers in English than in their native language, and Marin and colleagues (1983) showed that bilingual individuals provided more socially desirable answers in English (presumably because they were communicating to outsiders). These studies demonstrate the role that language plays in communicating the purpose of the study to people in different cultures. When surveying individuals across cultures, it is critical to consider the implications of language choice and make decisions based on input from local people. The committee believes that a disruptive technology forecasting system should not be limited to English, and participants should be able to express themselves and respond in their native language.

Copyright National Academy of Sciences. All rights reserved.

CONCLUSION

This chapter introduced the concepts of individual bias and forecasting bias and discussed their effects on the validity of a forecast and the ignorance that leads to the two forms of bias. Technology forecasts often suffer from bias due to inadequacies in the method of forecasting, the source of the data, or the makeup of those who develop the method. While some bias may be unavoidable, much of it can be identified and mitigated by developing a broad and inclusive forecasting system. The committee believes that the mitigation of forecasting bias requires periodic audits by internal and external evaluators to ensure the diversity of participants and data sources as well as the robustness of the forecasting process.

REFERENCES

Bennett, M. 1977. Response characteristics of bilingual managers to organizational questionnaires. *Personnel Psychology* 30: 29-36.

Bond, M.H., and M.K. Cheung. 1984. Experimenter language choice and ethnic affirmation by Chinese trilinguals in Hong Kong. *International Journal of Intercultural Relations* 8: 347-356.

Bond, Michael H., Kwok Leung, Al Au, Kwok-Kit Tong, and Zoë Chemonges-Nielson. 2004. Combining social axioms with values in predicting social behaviours. *European Journal of Personality* 18: 177-191.

Carstensen, Laura L., Derek M. Isaacowitz, and Susan T. Charles. 1999. Taking time seriously: A theory of socioemotional selectivity. *American Psychologist* 54(3): 165-181.

Costanza, Robert, Bryan G. Norton, and Benjamin D. Haskell. 1992. *Ecosystem health: New goals for environmental management.* Chicago, Ill.: Island Press.

Dooley, Kevin. 1996. A Nominal Definition of Complex Adaptive Systems. *The Chaos Network* 8(1): 2-3. Available at http://www.public.asu.edu/~kdooley/papers/casdef.PDF. Last accessed November 19, 2009.

Faber, Malte, Reiner Manstetten, and John Proops. 1992a. Humankind and the environment: An anatomy of surprise and ignorance. *Environmental Values* 1(3): 217-241.

Faber, Malte, Reiner Manstetten, and John Proops. 1992b. Toward an open future: Ignorance, novelty, and evolution. Pp. 72-96 in *Ecosystem Health: New Goals for Environmental Management*, Robert Costanza, Bryan G. Norton, and Benjamin D. Haskell, eds. Washington, D.C.: Island Press.

Fingerman, Karen L., and Marion Perlmutter. 1995. Future time perspective and life events across adulthood. *Journal of General Psychology* 122(1): 95-111.

Gelfand, M.J., J.L. Raver, and K. Holcombe Ehrhart. 2002. Methodological issues in cross-cultural organizational research. Pp. 216-241 in *Handbook of Industrial and Organizational Psychology Research Methods,* S. Rogelberg, ed. New York: Blackwell.

Gelfand, M.J., M. Erez, and Z. Aycan. 2007. Cross-cultural organizational behavior. *Annual Review of Psychology* 58: 479-514.

Hofstede, G., B. Neuijen, D.D. Ohayv, and G. Sanders. 1990. Measuring organizational cultures: A qualitative and quantitative study across twenty cases. *Administrative Science Quarterly* 35(2): 286-316.

House, Robert J., Paul J. Hanges, Mansour Javidan, Peter Dorfman, and Vipin Gupta, eds. 2004. *Culture, Leadership, and Organizations: The GLOBE Study of 62 Societies*. Thousand Oaks, Calif.: Sage Publications.

Huntington, S. 1996. *The Clash of Civilizations and the Remaking of World Order*. New York: Simon & Schuster.

Marin, G., H.C. Triandis, H. Betancourt, and Y. Kashima. 1983. Ethnic affirmation versus social desirability: Explaining discrepancies in bilinguals' responses to a questionnaire. *Journal of Cross-Cultural Psychology* 14(2): 173-186.

Ramos-Martin, Jesus. 2003. Empiricism in ecological economics: A perspective from complex systems theory. *Ecological Economics* 46(3): 387-398.

Schneider, Stephen, and B.L. Turner. 1995. Summary: Anticipating global change surprise. Pp. 6-18 in *Anticipating Global Change Surprises. A Report of the Aspen Global Change Institute Elements of Change Series*, John Katzenberger, and Susan Joy Hassol, eds. Aspen, Colo.: Aspen Global Change Institute.

Schwartz, S.H. 1994. Beyond individualism/collectivism: New dimensions of values. In *Individualism and Collectivism: Theory Application and Methods*. U. Kim, H.C. Triandis, C. Kagitcibasi, S.C. Choi, and G. Yoon. eds. Newbury Park, Calif.: Sage.

Sharma, Karan. 2008. Designing knowledge based systems as complex adaptive systems. Pp. 424-428 in *Frontiers in Artificial Intelligence and Applications*, Vol. 171, Wang Pei, Ben Goertzel, and Stan Franklin, eds. Amsterdam, Netherlands: IOS Press.

Copyright National Academy of Sciences. All rights reserved.

Simonton, Dean K. 1988. Age and outstanding achievement: What do we know after a century of research? *Psychological Bulletin* 104(2): 251-267.

Tellis, Gerard J. 2006. Disruptive technology or visionary leadership? *Journal of Product Innovation Management* 23(1): 34-38.

Triandis, H.C. 1972. *The Analysis of Subjective Culture*. New York: Wiley.

Triandis, H.C. 1983. *Essentials of Studying Cultures*. New York: Pergamon Press.

Waldrop, M. Mitchell. 1992. *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon & Schuster.

Copyright National Academy of Sciences. All rights reserved.

5

Ideal Attributes of a Disruptive Technology Forecasting System

One key objective of this study is to develop a forecasting approach that helps identify potential disruptions caused by technology that would have massive impact. Current methodologies for technology forecasting, such as those described in Chapter 2, are generally incapable of predicting extreme scenarios, especially those in which the most beneficial or catastrophic events occur. The committee believes that forecasters must look to the tail of the distribution curve of a technology's probability of emergence (at the time of prediction), since it is the locus of technological developments that are usually ignored and therefore hold the potential for surprise, as can be seen in Figure 5-1.

Many disruptions emerge when seemingly unrelated resources, people, events, and technologies converge. The ubiquity of the Internet, improvements in cost-efficiency of data storage, increasing processing power, and the globalization of trade and knowledge have converged to provide the opportunity for new tools, forums, and methods that will help identify emerging disruptions. These tools may allow scenarios to be tested in new ways.

This chapter aims to give a comprehensive description of the high-level goals and system characteristics for an ideal persistent forecasting system (the process flow is illustrated in Figure 5-2). An overview of the key tenets of a forecasting system is followed by a discussion of the relevant characteristics and examples of information sources feeding the forecasting system. Given the increasing size, scale, diversity, and complexity of data sets, information processing is of paramount importance. Data must be structured in such a way that automated systems can aid human analysts in recognizing new correlations and relationships. Given multidimensional forecasting output, selecting appropriate visualization schemes can also help human analysts to process complex output more quickly and creatively. Finally, as for any complex system, using and maintaining a persistent forecasting system yields a number of postprocessing and system management considerations, described in the final section of the chapter.

TENETS OF AN IDEAL PERSISTENT FORECASTING SYSTEM

Given the breadth, complexity, and dynamism of this project, it is useful to establish desired attributes to guide the development of a persistent forecasting system. Specifically, the system should have the following attributes:

- Persistence,
- Openness and breadth,
- Proactive and ongoing bias mitigation,

Copyright National Academy of Sciences. All rights reserved.

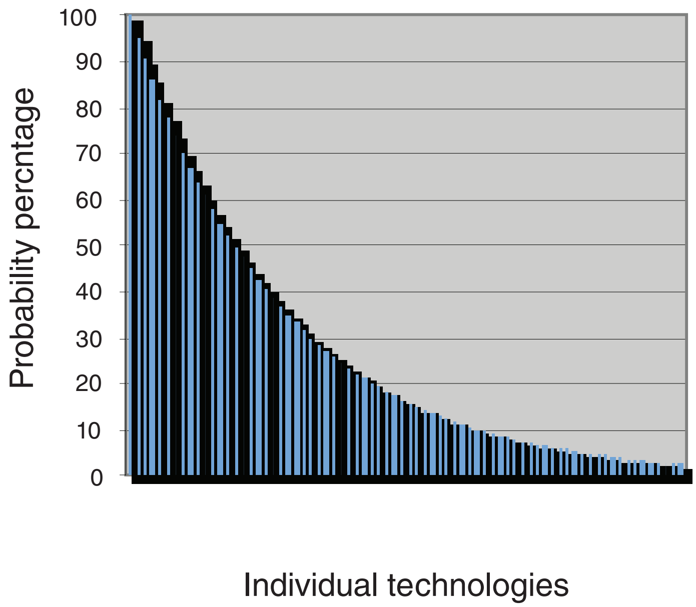


FIGURE 5-1 Probability of technology emergence.

- Robust and dynamic structure,
- Frames of reference for historical comparisons, and
- Ease of use.

Persistence

Persistence is one of the most important criteria to consider when designing a system for forecasting disruptive technology. Because most existing forecasts are developed over a short and finite time, they fail to incorporate signals that emerge after their creation and are therefore usable for only a short time. A key goal of a persistent system is to continuously improve the forecast based on new data, signals, and participant input. A persistent forecast can be built to serve many different customers, providing a continuously active and up-to-date forecast.

Openness and Breadth

No single group has the human, capital, or intellectual resources to imagine every possible disruptive scenario, capture every signal, or have access to all critical data. The persistent forecasting system must therefore be open to the widest possible participation. The more broad-based the system, the more likely it will be to generate many alternative futures and more extreme versions of the future, which often predict the most disruptive outcomes.

The committee believes that the entities running a persistent forecasting system need to be transparent and partner-friendly. This will build trust and yield compelling content and incentives that encourage broad and ongoing participation from a diverse (on every vector) group of participants.

The information derived from an open, persistent, crowd-sourced forecasting system can serve as a useful starting point for other classical approaches of forecasting, which in turn produce data and information to be fed back into the open system. Some forecasting methodologies can be employed to further investigate specific areas of interest and provide a deeper understanding of scenarios used to engage a targeted group for expert opinion. This approach uses both an iterative process, in which new ideas and forecasts are generated by crowds, and concept refinement, performed by experts. This feedback approach also exploits the strengths of other methodologies.

Copyright National Academy of Sciences. All rights reserved.

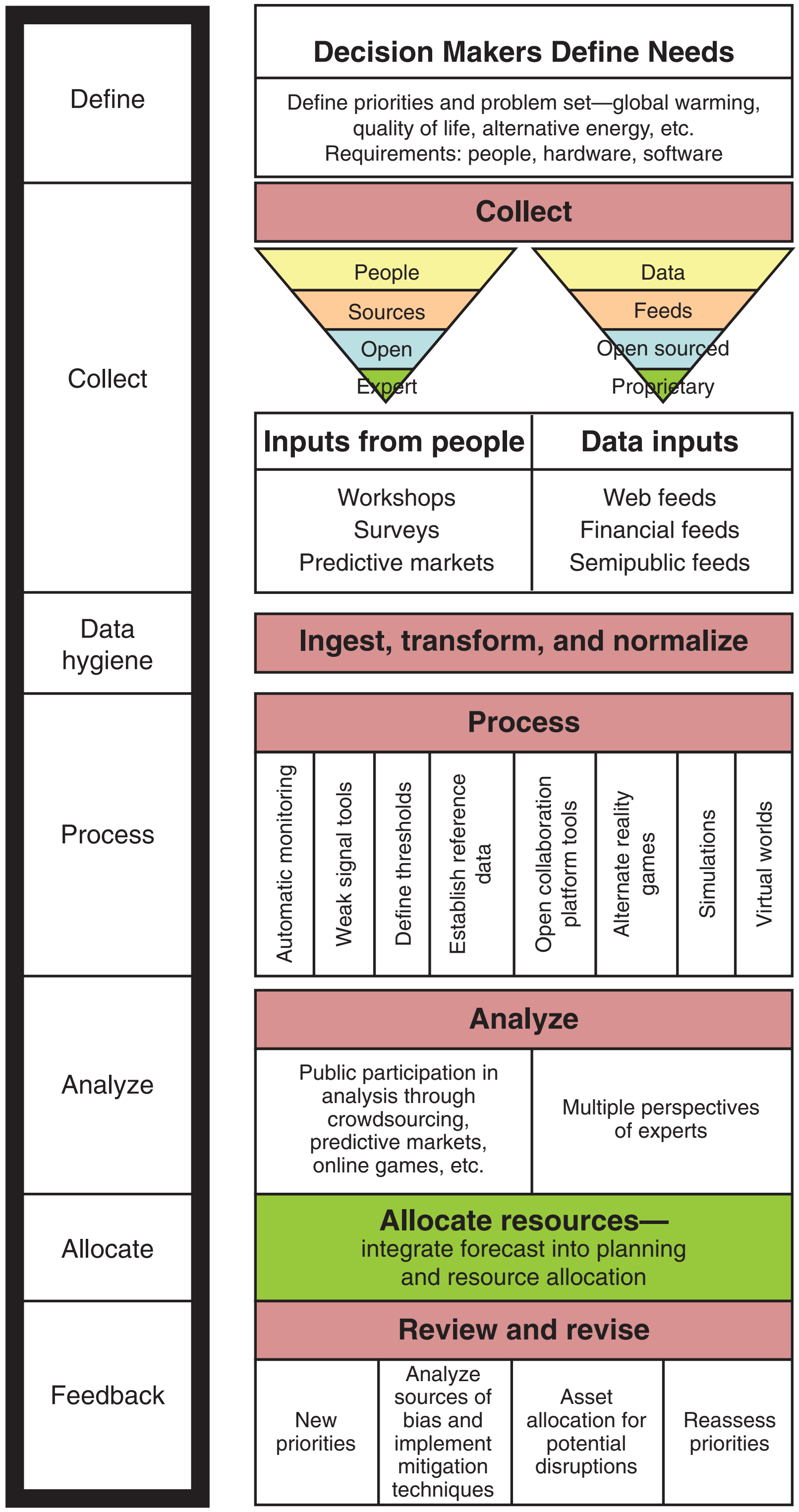


FIGURE 5-2 Conceptual process flow for the persistent forecasting system.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

Engage Both Crowds and Experts

Experts are typically better than novices at judging the importance of new signals in an existing forecasting system (Enis, 1995). With the currently available platforms (X2, Techcast, and Deltascan), experts generally provide high-signal and low-noise forecasts. However, academic research (Önkal et al., 2003) suggests that experts are not necessarily better at making forecasts than a crowd. Experts may not catch the full range of alternative solutions from adjacent fields outside their areas of expertise or from the reapplication of technologies developed to solve a different problem. Paradoxically, the narrowness of the knowledge specificity required to achieve expert status can invalidate forecasts generated by experts alone (Johnston, 2003). Thus, it is the committee's belief that blending input from experts and crowds will lead to better forecasts of disruptive technologies.

The goal of public participation, or crowd sourcing, in a forecasting system is to cast a wide net that gathers a multitude of forecasts, signals, and opinions. This is especially important as technology innovation becomes more diverse and geographically diffuse in its approaches and as regional variations of technology applications flourish. Collaboration technologies, especially those that leverage the power of the Internet, can be used to discover expertise in unexpected places.[1] Prediction markets, alternate reality games (ARGs), and relevant online communities are disseminating crowd-sourced methods.

Managing Noise in an Open System

Increasing the diversity of participants will increase the richness of a forecast. Nevertheless, open and public forecasting systems also present challenges to their operators. One of the challenges is the noise and distractions generated by such systems.

There are many different strategies for reducing the noise in crowd-based systems. Some systems limit participation to prescreened invitees. Screening is especially useful if a forecast seeks the opinions of a specific audience based on topic, region, or demographics (i.e., young European postdoctoral fellows studying quantum computing). Another approach is a completely open and public site, with fillers to select those with appropriate reputation, expertise, and credentials. Crowd-sourcing sites can use moderators who are themselves experts to monitor, moderate, and augment the forecasts and discussion. These moderators can be either internal staff members or volunteers from the community of users discovered through the Web.

Incentives for Contribution

It is important that a persistent forecasting system be not only open but also effective and relevant. For a system to generate enough signals and forecasts to be of value and to have adequate global representation, the operators must have a large number of diverse and active participants to cover the range of topics. This suggests that it should have adequate incentives (both financial and nonfinancial) to secure the ongoing participation of a diverse user base, to access technologically and socioeconomically impoverished contributors, and to persuade owners of proprietary data to donate (or sell) their data.

Spann and Skierra, as well as Servan-Schrieber and colleagues, suggested that the most effective incentives might be monetary or nonmonetary, depending on circumstances (Spann and Skiera, 2003; Servan-Schreiber et al., 2004). Incentives could utilize elements of gaming (competition), reputation, and financial rewards. Attention must be paid to the cultural appropriateness of the incentives used to secure reliable and valid data. Much of the world's population resides in collectivistic and hierarchical societies, where information is much more likely to be shared with one's own group[2] than with strangers (Triandis, 1995). An in-group is made up of people sharing similar interests and attitudes, producing feelings of solidarity, community, and exclusivity.[3] An out-group is made

[1]Available at http://itstrategyblog.com/whats-better-crowd-sourcing-or-expert-sourcing/. Last accessed May 6, 2009.

[2]In sociology, an "in-group" is a social group for which an individual feels loyalty and respect, usually because he or she is a member , while an "out-group" is defined as a social group for which an individual feels contempt, opposition, or competition. Available at http://en.wikipedia.org/wiki/Ingroup and http://en.wikipedia.org/wiki/Outgroup_(sociology). Accessed on April 14, 2009.

[3]Available at http://dictionary.reference.com/browse/ingroup. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

up of people outside one's own group, who are considered to be alien.[4] In collectivistic cultures, deception has been found to be more common among out-group members than in Western cultures (Triandis et al., 2001). In such cultures, financial incentives to share information might be less useful than symbolic incentives developed through contacts, with mutual commitment and obligations assured through connections within local networks.

Proactive and Ongoing Bias Mitigation

Bias in a forecast can create blind spots resulting in surprise. One way to reduce it is to continually ensure that ample data from a balanced and wide range of sources are used to create the forecast. Types of bias and techniques for bias mitigation are discussed in detail in Chapter 4.

Robust and Dynamic Structure

The world is a rapidly evolving, highly complex place with many interdependencies. This makes it difficult for decision makers to clearly define the parameters of forecasting disruption. Determining the cause and effect, as well as the precise timing, of interactions between technology and society is fraught with uncertainty as these interactions are nearly impossible to define in advance. Further, simplistic correlations are typically not useful, and the course of human events is frequently altered by unforeseen, random, and high-impact events. Therefore, the persistent forecasting system must be dynamic, flexible, and robust enough to embrace and incorporate great uncertainty, complexity, multiple perspectives, and sometimes unclear strategic imperatives.

Provisions for Historical Comparisons

Disruptions occur when trends are interrupted or when historical correlations or linkages among assets, people, or topics diverge. Looking for these disruptions requires that a system have adequate data to track historical and existing trends, as well as linkages to help users spot disruptions and discontinuities.

One useful frame of reference is to consider how disruptive technologies have developed and emerged historically. It would be useful to review the life cycle of a specific disruptive technology from concept, development, introduction, and adoption through maturity and obsolescence. Identifying key signposts, measurements of interest, and tipping points in the past would help us to recognize evolutionary patterns of development and some of the key inhibitors or enablers of disruptive technologies.

Another useful frame of reference would be to look back at the grand challenges in history and analyze how innovation and technologies were applied to overcome them. Understanding how initiatives and technologies failed to produce the kinds of disruptions originally hoped for by their creators can be just as important as understanding those that succeeded.

The system should include sufficient historical data to help researchers and forecasters to identify indicators of a disruption. Comparing such indicators against a baseline measurement of environmental and economic conditions may increase efforts to find and develop a new disruptive replacement for existing technologies. For example, understanding the threshold cost of gasoline and the necessary price performance ratio of alternative fuels and batteries would be useful for tracking a disruptive shift in propulsion systems for automobiles.

Ease of Use

To attract and maintain the broad participation of third parties, the system must have a robust set of processing and communication tools that are easy to use and accessible for partners, analysts, and participants alike. Function and ease of use for as diverse a population as possible must be designed into the system from the beginning. This should include a means for attracting users in languages other than English and a user-friendly graphical user interface.

[4]Available at http://dictionary.reference.com/browse/outgroup. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

INFORMATION COLLECTION

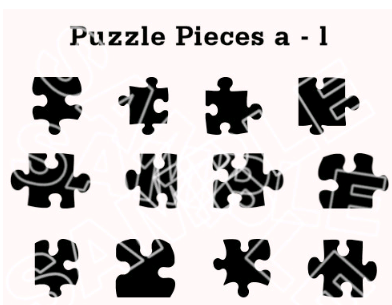
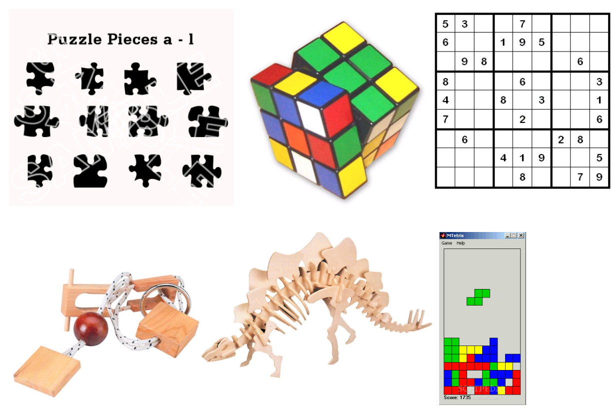
Understanding which data to collect or gain access to is an important step in building and maintaining a useful system. Gathering data for its own sake is neither useful nor productive and can result in information overload.

Considerations for Data Collection

Traditionally, there was a desire to collect all the necessary data over a fixed period and then to create a forecast once those data have been captured and ingested. However, this method can create epistemological bias (Faber et al., 1992) because it assumes ex ante that only a limited set of data connections and conclusions is possible. As for complex adaptive systems (CASs), it is not possible at any single point in time to identify all linkages and causalities or to model the consistent rational behavior of all the players and forces. Therefore, it is important to design a data repository that can be initialized with the relevant historical and current data sets and then populated with ongoing, real-time data collections (Jonas, 2006). This repository is used to create ongoing and on-demand forecasts.

The new forecasting system requires decision makers to have a different mental model of such a technology forecast. Instead of using a technology forecast to predict a single most likely scenario, the decision maker uses the system to understand the signals, signposts, and emerging picture of multiple alternative futures over time. Table 5-1 illustrates how the new system would compare to traditional forecasting models using a puzzle analogy.

TABLE 5-1 Puzzle Analogy

Type	Traditional Forecasting	New Forecasting
Visual		
Analogy	A single puzzle, pieces are known	Multiple puzzles, pieces distributed at random, media is inconsistent, tools required are unknown, assembler is blindfolded
Metaphor	One-time disruptive forecasting	Persistent disruptive forecasting
Context	A single best guess of a most likely future	Multiple alternative futures
Collection	It is possible to gather all the pieces	We don’t need all the pieces—just enough to see emerging patterns or pictures
Time	There will be time to run a dedicated processing step	Processing must be ongoing, as we cannot anticipate disruption

Copyright National Academy of Sciences. All rights reserved.

TABLE 5-2 Availability of Key Data for the Persistent Forecasting System

	Readily Available	Partially Available	Not Available
Digital	Ingest	Negotiate, collaborate, or create proxies	Create proxies
Nondigital	Negotiate digital rights (when necessary); digitize or manually input into machine-readable form	Negotiate, collaborate, or create proxies	Create proxies

Handling Data Overload

The cost of information collection, storage, processing, and dissemination has dropped consistently over the history of mankind. From stone engraving to cuneiform, scribes, the printing press, and now to the Internet, large data warehouses, and server farms, a society's ability to store, process, and disseminate information has increased dramatically (Blainey, 2002). Amazon's Elastic Compute Cloud (EC2) and Simple Storage Service (S3) and Google's App Engine exemplify the lowered cost of information storage and processing power. According to the 2003 Berkeley SIMS study *How Much Information?*, approximately 5 exabytes (5 million terabytes) of new information was created in 2002.[5] This is equivalent to approximately 800 megabytes per person, or 500,000 libraries the size of the U.S. Library of Congress print collection. One article estimated that Google stored just 0.02 percent of the world's information in 2006.[6]

Despite continued dramatic improvements in computational power, storage, and network connection speeds, there is still too much data stored in too many locations and too many data formats with various levels of accessibility (privacy, cost, language) and fidelity to allow simply blindly loading data into a persistent forecasting system. The more complex the data correlation, the more time and computational power needed to identify relationships. A data set of size n looking for two-factor correlations could theoretically take approximately n^2 computations, while a three-factor correlation would take approximately n^3 computations. For example, a dataset with 1 million elements could theoretically take 1 trillion computations to analyze all of the two-factor correlations, while a process of trying to find three-factor correlations could take up to one quintillion (10^{18}) calculations. Therefore, it is important that the data prioritization and structuring processes are done before the data are gathered.

Persistent and systematic data gathering is an essential step in assembling a persistent disruptive technology forecasting system. The good news is that the information available on the Internet grows with every passing moment. However, this suggests that the forecasting system will also need to consider data source prioritization and filters to eliminate duplicative or less relevant sources. Further, it is important to complement online data extraction with classical methods of information collection to supplement and validate online data in an efficient and judicious manner.

Collection Limitations

Some pieces of information critical to the persistent forecasting system may be in a format not easily extractable or translatable, may be proprietary, or may not be available electronically or at all, as shown in Table 5-2. The operators of the persistent forecasting system should, accordingly, be creative in improving the accessibility of viscous data or in creating proxie*s* (substituted information sources) where data are not otherwise available.

Depending exclusively on digital data collections is not sufficient. Indeed, a significant portion of the world's population remains offline, for reasons including poverty, lack of electronic accessibility, legacy systems, or a desire to remain anonymous. As a result, classic data-gathering techniques such as workshops, article reviews, document collection, and first-hand interviews or reporting are still critical. These efforts should be pursued on a cost-effective basis to serve areas where there is a known lack of information, a need for bias mitigation, or when scope broadening is required.

[5]A 3-year study started in 2008 to determine how much information there is in the world is being undertaken at the Global Information Industry Center at the University of California, San Diego. Available at http://hmi.ucsd.edu/howmuchinfo.php. Last accessed May 6, 2009.

[6]Available at http://www.knowledgebid.com/media/blog/google-225b-and-02-percent/. Last accessed October 23, 2008.

Copyright National Academy of Sciences. All rights reserved.

There are any number of reasons why data might be only partially available, including rights to use, fees, language, format, digital or analog, and matters of privacy and ownership. The operators of a persistent forecasting system should consider a number of ways to access partially available data. When relevant data are in a foreign language, operators might consider employing context and translation tools or use crowd-sourcing techniques to translate. Translation tools, while not perfect, continue to improve, making data in foreign languages more available. The quality of existing commercial and open source extract, transform, and load (ETL) tools continues to improve, making it increasingly possible to extract information from different (particularly unstructured data) formats. In other cases, it might be possible to negotiate better terms for commercial databases or to create or join open collaboration communities. Finally, it may be necessary to digitize and manually enter data if it is not already available in electronic form.

It is anticipated that there will be a number of subject areas where information is not readily accessible, probably owing to gaps in coverage. Statistical analysis might show which certain regions of the globe systematically report less information than expected. It is anticipated that there will be similar underreporting for technologies that show promise but for which there remains insufficient publicly available information. In other cases, it may be impossible to find or access the data for reasons of confidentiality or other factors. In these situations, the persistent forecasting system operators should consider utilizing proxies. For instance, the pricing of certain key raw materials may not be publicly available. In this situation, it may be necessary to negotiate with the supplier(s) of that raw material for access to information. Failing that, operators of the persistent forecasting system might consider creating a proxy consisting of key production inputs of the raw material, collaboration communities, or predictive networks.

Key Characteristics of Information Sources

In selecting information sources to use in a persistent forecasting system, the operator must first ask whether the data have the following characteristics (sources that score above average in several characteristics may be more useful than those that score very high in only one or two characteristics):

- Can be evaluated anywhere,
- Updated regularly,
- Relevant,
- Quantifiable,
- Sources are accurate and attributed, and
- Source has a good reputation.

Jonas points out that data warehouse operators must keep track of data source characteristics, but should be careful to not exclude data because of poor quality characteristics.[7] Changes in the quality of information and the emergence of new data sources may in and of themselves be a sign of pending disruption.

Globally Evaluable

An inherent requirement for the persistent disruptive forecasting system contemplated by this report is the ability to evaluate information on a global basis, making it important that the information gathered be globally sourced. A quantitative measurement of this characteristic would be a chi-squared distribution ranking the amount of information created by a country in comparison to a number of factors including but not limited to that country's overall population, its university population, gross domestic product (GDP), number of patent applications, published scientific papers, and R&D investment.

[7]Personal communication with Jeff Jonas, Chief Scientist of the IBM Entity Analytics group and an IBM Distinguished Engineer. See information available at http://www.research.ibm.com/theworldin2050/bios-Jonas.shtml. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

Regularly Updated

To forecast persistently, continuous sources of new information are necessary. In general, data may be persistently or periodically available or available once only. A data set collected once is less useful than a data set that will continue to be generated over time. Such persistence will allow for the data to be tracked, evaluated, and trended over time. The persistence of an information source would be measured as the standard deviation of quantity or the value of data sets created year by year.

Comparative Relevance

Relevance is difficult to determine, particularly when attempting to forecast future events that are disruptive in nature. It must be thought of as a relative measure for allocating scarce analytical capabilities. It is a challenging issue because some of the best signals are those not likely to be viewed as acceptable or mainstream. Nevertheless, one potential measure of relevance is how it affects a potentially disruptive technology, directly or indirectly.

Comparative Quantifiablilty

Given the massive amount of data that exists and the ever-growing number of tools and methods for analyzing the world around us, there are few realms that are not quantifiable. This characteristic, similar to relevance, must be used relatively. For example, use of the words "semipermeable membranes are important" by a single writer is not quantifiable. However, an increase in the number of writers using those words, from 1,750 in 2009 to 2,000 writers in 2010 in a community of 20,000 experts, could be a very useful quantitative measure.

Accurate and Attributed Sources

When gauging the accuracy of a source, it is important to ascertain where the data in the source came from. Anonymous information may be correct, useful, and valid, but care must be taken to ensure that it is not deliberately misleading. There are also cases where a large number of sources agree but are incorrect (e.g., observations of the Loch Ness monster). The accuracy of the data from a source can be measured by understanding the basic attributes of the source and tracking its output over time to determine if the earliest data were correct.

Source Reputation

One measure of a source's trustworthiness is its reputation. Reputation can be assessed by examining the number of times information from a source is cited in other credible works. Google's PageRank is based on the principle of citation analysis,[8] which is not, however, perfect. If it is not applied appropriately, citation analysis can be biased, perpetuating current thinking and conventional wisdom. Openness, peer review, and certification by a trusted third party are also important to minimize bias and engender trust in a forecasting system. An information source should be considered more trustworthy if it allows outsiders to challenge and review its methodology for collection, data hygiene, and management.

Potential Sources of Information

There are many sources of potentially useful data available to the public. They include the Beige Book,[9] government reports from around the world, and other reports issued by nongovernmental organizations (NGOs),

[8] More information available at http://en.wikipedia.org/wiki/Bibliometrics. Last accessed May 6, 2009.

[9] The *Summary of Commentary on Current Economic Conditions,* commonly known as the Beige Book, is published eight times per year. Each of the 12 Federal Reserve Banks gathers anecdotal information on current economic conditions in its district from the reports of Bank and Branch directors and interviews with key business contacts, economists, market experts, and other sources. The Beige Book summarizes this information by district and sector. Available at http://www.federalreserve.gov/fomc/beigebook/2009/. Last accessed August 10, 2009.

Copyright National Academy of Sciences. All rights reserved.

TABLE 5-3 Questions Posed to Data Sources at Different Phases of Inspection

Phase 1 Questions	Phase 2 Questions
Is this field currently experiencing disruption? Who is gaining in the field and who is being displaced? Which factors are driving this disruption? Which disruptive technology (if any) is enabling this disruption? Which can be used to mitigate or amplify the disruption? Which new phrases, terms, or other indicators are associated with this disruptive technology and disruptive field?	Who stands to gain and who is the most at risk should a disruption occur? Could technology play a role in disrupting this field? Are technology investments being made that target this field? If so, • How much is being invested? • How many research personnel are pursuing the technology of interest? • How many man-hours are expended in this area each week? Each month? Each year? • Which nations are pursuing these potentially disruptive technologies most aggressively? • Which natural resources are enablers of these disruptive technologies? • Which phrases, terms, or other indicators are used to describe a potential disruption of this field?

research organizations, corporations, trade organizations, universities, open source consortiums, online S&T repositories, and S&T Web sites. Given the broad range of technologies that are the focus of this report and the need to anticipate disruptive technologies and events, including those that might be considered to have a low probability of occurrence but high potential impact, it is essential that collectors maximize their collection resources effectively, utilizing traditional as well as more novel sources of data.

Furthermore, information must be gathered with an eye to answering two similar yet distinct questions: (1) How do you identify fields that are being disrupted as well as fields that could be prone to disruption (Phase 1 question)? (2) How do you monitor how far those fields have progressed toward disruption (Phase 2 question)? Some of the questions that might be posed to these data sources are listed in Table 5-3.

The information sources described in the remainder of this section may be of interest and could be useful to a disruptive technology forecasting system.

Trade Associations and Magazines

According to Wikipedia, there are over 7,600 trade associations in the United States.[10] Las Vegas, Nevada, is estimated to have hosted at least 624 trade shows in 2008, with over 2,000,000 total attendees.[11] If each trade association generated just one piece of searchable literature outlining market and technological trends, together they would constitute a robust source of information. Further, as trade associations are an outcome of broad, industry-wide initiatives, they tend to present information in a manner that is particularly well suited to the goals of a persistent forecast.

Universities and Cooperative Research Centers

The 1,150 accredited colleges and universities in the United States collectively educate almost 5,000,000 students per year.[12] The National Science Foundation has sponsored 71 industry and university Cooperative

[10]Available at http://en.wikipedia.org/wiki/Industry_trade_group#cite_note-0. Last accessed October 23, 2008.

[11]Count of calendar events as of August 1, 2008, from the Las Vegas Tourism Bureau Web site. Available at http://www.lasvegastourism.com/index.html. Last accessed October 23, 2008.

[12]Available at http://www.aacu.org/about/index.cfm. Last accessed October 24, 2008.

Copyright National Academy of Sciences. All rights reserved.

Research Centers, 47 of which remain active.[13] These centers foster collaboration between universities and industry. To monitor and understand the inner workings of these research centers would require a significant, but not extraordinary, amount of work and configuration during the initial construction stages of a persistent forecasting system. It is imperative to gather information about universities and centers of excellence because they are hubs for many global technology clusters.

A simple understanding of college and university graduation rates would provide insight into areas of growing importance. Another approach is to track the number of times a program or facility is referred to on the Internet.[14] Most universities and colleges throughout the world post information about their institutions on the World Wide Web. Braintrack.com, an online directory of the world's universities and colleges, lists and provides links to more than 10,000 universities in 194 countries. Similar support should be made available for institutions carrying out research in disruptive technologies.

Academic Papers

Nearly 3 million scientific papers were published in the United States across all fields between 1996 and 2006.[15] Worldwide, this number was nearly 8 million over the same time period, resulting in 800,000 papers per year that could be analyzed and incorporated in a persistent system. Using Zipf's law or other power-law distributions of paper citations, it should be possible to observe how the importance of a paper changes as references to it increase over time (Gupta et al., 2005).

Financial Data

There is no shortage of financial information. Financial data are so pervasive that many novel methods of finance are back-tested and applied to historical financial information, such as cotton prices in the 1800s, rather than tested using current information (Mandelbrot, 1963). The total value of all globally traded public securities is estimated to be $51 trillion.[16] The United States alone has over 17,000 public companies.[17] Each of these public companies produces detailed quarterly financial reports and public disclosure statements, as well as significant amounts of data on pricing and volume of trades.

Public equities are not the exclusive source of potentially valuable information; unlisted securities may hold more information if it is available. The National Venture Capital Association says that $7.4 billion was invested in early stage companies through 977 transactions during the second quarter of 2008 alone.[18] Similar information is available on European and Australasian venture capital from the European Private Equity and Private Venture Capital Association and the Australian Private Equity and Venture Capital Association. However, as is the case with public securities, financial information on private/venture capital is more easily gathered on domestic than on overseas markets.[19]

Commercial Databases

There are many commercially available databases. One example is ProQuest, which has archived and made searchable over 125 billion digital pages of information and works with over 700 universities to distribute over 60,000 dissertations and theses a year on their online database. Questia allows access to over 2 million books, articles, and journals, while competitor HighBeam Research has over 60 million peer-reviewed papers represent-

---

[13]Available at http://www.nsf.gov/eng/iip/iucrc/directory/index.jsp. Last accessed October 24, 2008.

[14]International Colleges and Universities is a Web site that lists 8,750 accredited colleges and universities around the world and ranks the top 200 based on Internet references. Available at http://www.4icu.org/. Last accessed May 6, 2009.

[15]Available at www.thomson.com. Last accessed November 11, 2008.

[16]As of August 18, 2008. Available at http://en.wikipedia.org/wiki/Stock_market. Last accessed October 24, 2008.

[17]Available at http://answers.google.com/answers/threadview?id=543247. Last accessed October 24, 2008.

[18]Available at www.nvca.org. Last accessed October 23, 2008.

[19]Available at http://www.evca.eu/ and http://www.avcal.com.au/. Last accessed October 24, 2008.

Copyright National Academy of Sciences. All rights reserved.

ing over 3,500 publications, 1,500 of which are academic. There is no shortage of associations and organizations that make their own materials publicly available: the *Journal of the American Medical Association* (JAMA), the *British Medical Journal* (BMJ), and the U.S. Patent and Trademark Office all have searchable online databases, as do countless others. While the ability to immediately tap into large databases is a great asset, it does have one glaring deficiency—the bulk of online publications are in English. Although non-English databases exist, most notably at China.Eastview.com, foreign language listings are smaller and scarcer than holdings in English. Although English is currently the primary language of scientific publication, the committee believes focusing exclusively on data holdings in English would introduce additional bias and lead to missed opportunities.

Blogs

Blogs are the social postings of individuals. As blogs have grown in sophistication, the difference between the page of a news organization and the page of a regular and sophisticated blogger has become less clear. While counting the members of the blogosphere was long an important measure of the Web's vibrancy, such counting efforts appear to have decreased over the past year as the medium's growth soared, making the task much more difficult. The most commonly referenced measure is provided by Technorati; its most recent assessment, posted in 2007, indicated it was tracking 112 million blogs.[20] A large and diverse data set could be created from the content of these blogs.

Blogs are as important as other written records like books, magazines, or even graffiti because they allow researchers to access the impressions of others. There are problems with blogs, such as false reporting, but these are biases that can be accounted for. Further, the fact that they are published online allows them to be electronically gathered, searched, and analyzed.

Crowd-Sourced Content

Much online crowd-sourced information could be useful to analyze. The best known example is Wikipedia, which is estimated to have taken 100 million hours of thought to achieve its current state (Shirkyon, 2008). Wikipedia has over 75,000 contributors, who together have created over 10,000,000 articles in over 250 languages. Nearly one quarter of these articles are in English.[21]

Social Networks

Social networks allow us to observe the relationships between members and to observe how members self-classify. Currently, Facebook has 200 million active users and is the fourth most visited site on the Web.[22] It is also the largest photo sharing application. There are 55,000 communities within Facebook, representing different schools, regions, workplaces, and other groups.[23] Other social networks include MySpace, which attracts 115 million international users,[24] and LinkedIn, a career-oriented site with over 16 million users.[25] Xiaonei has 34 million Chinese users[26] and 51.com has 26 million Chinese users.

[20] Available at http://technorati.com/. Last accessed August 1, 2008.
[21] Available at http://en.wikipedia.org/wiki/Wikipedia:About. Last accessed October 24, 2008.
[22] Available at http://www.facebook.com/press/info.php?statistics. Last accessed May 6, 2009.
[23] Available at http://www.facebook.com/press/info.php?statistics. Last accessed October 24, 2008.
[24] Available at http://www.techcrunch.com/2008/06/12/facebook-no-longer-the-second-largest-social-network/. Last accessed May 6, 2009.
[25] Available at http://venturebeat.com/2007/12/09/linkedin-launches-platform-redesign-a-better-business-social-network/. Last accessed May 6, 2009.
[26] Available at http://www.socialnetworkingwatch.com/international-social-netw.html. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

Patents

Patents are a potentially interesting source of information. Since 1836, the U.S. government has issued more than 6,500,000 patents. Roughly 300,000 patents are filed in this country each year. Moreover, patents are a global phenomenon, with Japan regularly topping the United States in the number of global applications and the United Kingdom, Germany, and other European Union countries often applying for more than 200,000 patents annually.[27]

Despite the potential promise, the committee recognizes that patent filings and patent awards have weak correlations. Today, many companies rush to patent innovations that may not result in success, and it is estimated that companies use less than 2 percent of the patents that they file. Also, given the slow speed of patent issuances relative to the speed with which disruptive venture-backed technologies are adopted, many companies become wildly successful before patents are actually issued, if they are issued at all. Nevertheless, analysis of patent applications can reveal trends, patterns, clusters, and novel applications of technologies.

Cross-Cultural Data Collection

Collecting data from different cultures is by no means straightforward, and the potential for injecting bias into the data and the resulting forecast is significant. Some techniques for successfully gathering information as well as some concerns about cross-cultural data collection are discussed below.

Surveys

Surveys are frequently used to collect data on potentially disruptive technologies in different cultures. Yet challenges to cross-cultural surveys abound, including the difficulty of motivating people to engage in such surveys, making survey instructions understandable, and measuring the validity and reliability of responses.

For example, while surveys are popular for assessing attitudes in this country (Kuechler, 1998), asking individuals to fill out questionnaires is not as familiar or appropriate elsewhere. Several characteristics of U.S. culture coincide with the requirements of the individual survey methodology, including the emphasis on individualism, freedom of speech as a basic right of all citizens, high literacy rates, the willingness of individuals to participate, comfort with expressing opinions, and familiarity with the testing format.

Clearly, not all cultures have these characteristics (Kuechler, 1998; Greenfield, 1997). It may be necessary for the researcher to adapt the survey instrument for each culture so that it is appropriate and comprehensible for members of that society. Pilot testing and discussion with local collaborators are critical to ensuring that a particular method is appropriate for other cultures.

Interviews and Focus Groups

Interviews and focus groups enable researchers to gain depth of knowledge on a particular topic. However, difficulties may arise in standardizing interviews across cultures. The characteristics of an effective interviewer might vary across cultures—for example, women interviewing men could be viewed as inappropriate, and ignorance of this taboo could invalidate interview results. Pareek and Rao (1980) argue that the background of an interviewer be considered to elicit genuine and unbiased answers from respondents. The background of an interviewer can influence rapport and cause the interviewee to self-disclose more or less, depending upon his or her comfort with the interviewer. In Günther's research with international families in Saudi Arabia (1998), months of relationship-building with local collaborators and government officials were necessary to gain access to families in the community. This example points to the importance of cultural sensitivity and good relationships when working in other cultures.

[27]Available at http://data.un.org/Default.aspx. Last accessed August 1, 2008.

Copyright National Academy of Sciences. All rights reserved.

Cultural Documents

Cultural documents, including newspapers, speeches, and proverbs, provide useful and unobtrusive cross-cultural data for analysis. For example, Weber and colleagues (1998) analyzed historical proverbs to understand the psychology of risk in other cultures. When analyzing the content of such documents, researchers should ask local collaborators to assist with taxonomy and to identify the documents most relevant to the research topic. This would ensure the comparability of documents across cultures and aid in the development of coding schemes that produce reliable and valid results for a culturally diverse data set.

Observations of Behavior

Simple observations of behavior provide another unobtrusive method for collecting cross-cultural data. Researchers should confer with local collaborators to ensure that the observation is interpreted properly.

Databases

Existing cross-cultural databases may also contain useful data, but they need to be examined with care. Such databases may label, structure, categorize, or assess constructs differently than databases gathered at home in the United States, and their measurements may be biased. In such cases, there may be no existing data dictionary with which to associate related content. Taxonomies will need to be created to assist extraction, transformation, and loading (ETL) tools to produce useful data ready for processing.

Data Preprocessing

One of the biggest challenges for the operators of the persistent forecasting system will be translating data from multiple sources into a single format that permits analytical and visualization tools to mash up data sets and adjust parameters seamlessly. Data feeds will need to be ingested, transformed, and then normalized before further processing and decision making can occur.

Data Organization

There are two principal methods for organizing large data sets: relational databases (RDBs) and the resource description frameworks (RDFs). Both have their place in any large data-processing project; however, implementation of RDF could prove particularly valuable to a persistent forecasting project because the data sources and formats tend to be more heterogeneous and dynamic:

- *RDB*. These fit the static model that has most often been followed in past forecasting efforts. Data are defined in set fields, assembled in tables, and relationships described using a relational model termed a schema. Business analytic tools are then used for identifying correlations between objects and their descriptive fields. RDBs have been in use since the early 1970s. Their principal advantages are that they are well known, well understood, commonly accepted, well supported by analytical tools, and have large populations of professionals experienced in their construction and operation. Unfortunately, they may be slow in their analysis and require a significant amount of description, structuring, and coaching to fully realize their benefits. Once structured, RDBs are a fast, efficient, and effective way to manage large structured databases.
- *RDF*. This is a novel approach to database management that evolved from the meta content framework (MCF) originally pioneered at Apple Computer in the mid-1990s.[28] Joshua Tauberer (2008) describes RDF as

[28]Available at http://en.wikipedia.org/wiki/Meta_Content_Framework. Last accessed October 23, 2008.

Copyright National Academy of Sciences. All rights reserved.

> the standard for encoding metadata and other knowledge on the Semantic Web. In the Semantic Web, computer applications make use of structured information spread in a distributed and decentralized way throughout the current web.

The Semantic Web is a decentralized framework for distributed information. RDF is the World Wide Web Consortium's standard for encoding this information.[29] The main architecture behind RDF is the concept of the "triple," the relationship between the subject, predicate (verb), and object of a clause. Because the RDF protocol is more straightforward and requires less structuring than that of the RDB, it can be learned and processed more quickly by automated systems.[30] Although newer than RDB, RDF is a proven technology. The University of Maryland's T-REX (The RDF EXtractor) has already processed 32.3 million articles and processes up to 150,000 additional articles per day (Subrahmanian, 2008).

Processing Unstructured Data

It has been estimated that 80 to 90 percent of all potentially usable business information originates in unstructured form.[31] Similarly, the World Wide Web is primarily made up of unstructured data. Unstructured data are data that do not conform to a data model and are therefore not easily manipulated by computers. Wikis, Web pages, and blogs are generally unstructured.

There are several techniques that can be used to analyze and index unstructured data, including text data mining, text analytics, and link analysis. Many of these approaches use statistical methods such as latent semantic indexing (LSI) and Bayesian modeling, and some require training sets and taxonomies to increase their accuracy. Domain-specific ontologies[32] can be created to reduce semantic inconsistency. Database managers are developing schemata to electronically extract, transform, and load unstructured and narrative data into their datamarts.[33] Many companies now use a range of technologies to process unstructured data.

Companies like Google, IBM (Webfountain[34]), and Microsoft (Bing) have built automated systems to ingest billions of Web pages (including wikis and financial data) of unstructured data several times a day. These systems process information included in key content tags and attribute lists. Companies like Technorati use tags that bloggers and other content authors place on their Web sites and, with the help of categorization technologies, index millions of blog posts in real time and can recall them in seconds using headlines and tag clouds.[35]

Factiva, a division of Dow Jones & Company, produces tools and resources for search, semantic analysis, and controlled vocabularies that access more than 25,000 authoritative sources[36] (such as newspapers, journals, magazines, news and radio program transcripts) from 152 countries in 22 languages, including more than 120 continuously updated newswires.[37]

Text analytic companies such as ClearForest provide text analysis and data mining technologies designed to convert unstructured data into structured data. ClearForest tags key concepts hidden in unstructured text. Once tagged, this information can be entered into structured databases and used to identify trends, patterns, and complex interdocument relationships within large text collections and create links with other structured data.

Attensity has developed a suite of commercial applications that combine natural language processing and semantic technologies to transform natural language into structured data. They combine statistical methods and

---

[29]Available at www.xml.com/pub/a/2001/01/24/rdf.html. Last accessed May 6, 2009.

[30]Available at http://en.wikipedia.org/wiki/Resource_Description_Framework. Last accessed October 23, 2008.

[31]Clarabridge, 2008, unstructured data and the 80 Percent rule, *Bridgepoints* (23).

[32]An ontology is a formal representation of a set of shared concepts within a domain and the relationships between those concepts. Available at http://en.wikipedia.org/wiki/Ontology_(information_science). Last accessed July 19, 2009.

[33]Available at http://www.dbazine.com/datawarehouse/dw-articles/lewis4. Last accessed July 16, 2009.

[34]Available at http://en.wikipedia.org/wiki/IBM_WebFountain. Last accessed July 16, 2009.

[35]Tag clouds are visual presentations of tags, in which the size, weight, or color of the tag can be used to represent features (e.g., frequency, importance, sentiment) of the associated terms. Available at http://en.wikipedia.org/wiki/Tag_cloud#cite_note-0. Last accessed July 19, 2009.

[36]Available at http://factiva.com/about/index.asp?node=menuElem1098. Last accessed July 16, 2009.

[37]Available at http://en.wikipedia.org/wiki/Factiva. Last accessed July 16, 2009.

Copyright National Academy of Sciences. All rights reserved.

technologies (including keywords, classification, clustering, categorization, machine-learning, case-based reasoning, name entity recognition, language identification, event and relationship extraction, and artificial intelligence) with linguistics methods and technologies (such as exhaustive extraction, advanced pattern recognition, and the Semantic Web) for the discovery, management, and analysis of unstructured data.[38]

Wolfram|Alpha, a new knowledge engine, uses a hybrid approach depending on computation to access and process trillions of pieces of curated information. It blends supercomputer computation, human curation, and directed modeling.

By using text analytic and semantic technologies, a forecasting system can electronically "crawl" and index millions of pages of unstructured text from targeted Web sites, blogs, wikis, scientific and technical papers, and published works. The committee believes that appropriate scientific and technology ontologies can be created to help reduce semantic inconsistency between bodies of unstructured text collections. These texts can then be analyzed to highlight the appearance of new scientific and technical concepts, the emergence of new applications, and changes in sentiment that can be used as disruptive technology forecasting signals.

The committee believes that employing crowd sourcing in a forecasting system requires a method for structuring vocabulary in order for the system to convey meaning and to facilitate conversations across a diverse group of users. This is also important to enable computers to more easily process, organize, and retrieve unstructured portions (e.g., blogs, wikis, tweets,[39] and user comments) of the data. One approach is to use a "controlled vocabulary," a common and generally agreed upon task-specific list of words, phrases, and acronyms to describe or tag text, images, and objects. Controlled vocabularies are used in subject indexing schemes, subject headings, taxonomies, thesauri, and ontologies.

Semantic Web technologies address the need for controlled vocabularies. The Semantic Web is an evolving development of the World Wide Web in which the semantics of information and services on the Web are defined, making it possible for requests of people and machines that use Web content to be easily understood and satisfied.[40] A forecasting system that incorporates crowd casting and relies on unstructured Web-based input should incorporate Semantic Web technologies.

The Semantic Web standard RDF and RDF Schema provide the infrastructure for making vocabularies available as resources on the Web for anyone to reference and use. RDF is a language for representing information about resources on the World Wide Web. It is intended for use where information needs to be processed by applications rather than being displayed only to users.[41] RDF employs an established system for global naming, the uniform resource identifier (URI), which is in current use on the Web.[42]

INFORMATION PROCESSING

When seeking the reason a person or group of persons failed to foresee a particular catastrophic event, such as the terrorist attacks of September 11 or the collapse in 2008 of the Lehman Brothers financial services firm, it often turns out that all of the necessary information was available but that larger patterns and conclusions were missed by the time a subset of that information had been processed and passed on to key decision makers. Appropriate and intelligent processing of multiple information streams (as described in the preceding section) is essential for accurate forecasting.

Operators of pervasive forecasting systems require a set of processes to ensure that only relevant and useful information is presented and that aggressive efforts are made to organize and present information in a way that improves human cognitive processing capabilities. The challenge is to determine which tools and methods can be used to identify disruptions.

[38]Available at http://www.attensity.com/en/Technology/Semantic-Engines.html. Last accessed July 19, 2009.

[39]Tweets are 140-character text posts used by the Twitter microblogging service.

[40]Available at http://en.wikipedia.org/wiki/Semantic_Web. Last accessed July 17, 2009.

[41]Available at http://www.w3.org/TR/REC-rdf-syntax/. Last accessed July 17, 2009.

[42]Available at http://www.semanticuniverse.com/topquadrant-monthly-column/group-blog-entry-semantic-web-key-enabler-enterprise-vocabulary-management. Last accessed July 17, 2009.

Copyright National Academy of Sciences. All rights reserved.

Trends to Track

An understanding of complex systems is critical for forecasting disrupting technologies. In general, complex system behavior is determined by the interaction of agents among themselves (either dampening or reinforcing connections) or by their response to an external stimulus. The agents in a forecasting system are humans from around the globe. Tracking emerging trends, abnormal behaviors, or catalytic events (such as September 11, 2001) that take place in a variety of scientific, natural, and social systems is a key requirement.

Systems theory is the interdisciplinary study of complex systems in science, nature, and society.[43] While many factors ultimately contribute to disruptions, the committee believes that because at least one, if not all three, complex systems are present in most disruptive technologies, the ideal forecasting system should, at a minimum, incorporate robust scanning and monitoring methodologies to detect variations in the rate of change for the following:

- Science and technology discovery,
- Trends in nature, and
- Societal trends (including economics, law, policy, and the arts).

Science and Technology Discoveries

It is critical that a persistent forecasting system track research and investment breakthroughs, progress in science and technology, and S&T applications. According to Peter Schwartz in *The Art of the Long View* (1991, p. 62), S&T discovery

> is one of the single most important drivers of future events. It literally shapes the future. Politics can change, but a scientific innovation, once released into the world, cannot be taken back. Nor can its impact be legislated away or forbidden by the chairman of the board. Thus keeping track of new developments in physics, biotechnology, computer science, ecology, microbiology, engineering and other key areas is a special duty.

A significant portion of S&T research and development is in the public domain and is quickly becoming more accessible owing to the growth of the Internet. There are a number of relatively robust science-dedicated search engines, wikis, and publication sites that can be use to access, search, and index scientific papers. These papers can then be incorporated and analyzed using bibliometric techniques.[44]

Some scientific and technical R&D and a significant amount of application development is not disclosed to the public and resides in the R&D labs and departments of large technology, life science, energy, and pharmaceutical corporations; start-up companies; and classified government laboratories. The forecasting system may allow developing proxies for undisclosed scientific research, development, and application. Some proxies that should be considered include patent filings; scientific funding from venture capital or research grants; and knowledge gleaned from industry conferences, trade associations, trade magazines, and sector-specific interviews or workshops.

A persistent forecasting system should monitor relevant Web sites, blogs, publications, and periodicals for new words and terms that appear in specific scientific domains. One approach is to track the introduction of new tags in controlled vocabularies. New scientific and technical words and terms could be important forecasting signals.

Trends in Nature

It is also important to consider key trends in nature and how they might enable or inhibit technological disruptions. Which raw materials are necessary for a healthy economy? How long will remaining natural resources last? What factors, such as a dramatic rise in ocean levels, could affect the accessibility of these resources or popula-

[43]Available at http://en.wikipedia.org/wiki/Systems_theory. Last accessed October 23, 2008.

[44]Bibliometrics is a set of methods used to study or measure texts and information. Citation analysis and content analysis are common bibliometric methods. Available at http://en.wikipedia.org/wiki/Bibliometrics. Last accessed July 17, 2009.

Copyright National Academy of Sciences. All rights reserved.

tions, cities, and the infrastructure? What are the likely impacts of potential disasters such as global warming or sudden deforestation?

The persistent forecasting system may deploy sensors and collaborate with organizations to monitor trends in nature, natural resource availability, and scientific discovery. Agencies and organizations such as the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Agency, the National Centre for Medium Range Weather Forecasting (India), the National Weather Service, the National Seismological Agency, the World Wildlife Fund, and the Natural Resources Defense Council, among others, may offer important insight into early signals of change. However, because many of these organizations have polarizing viewpoints, a persistent forecasting system should consider inputs from individuals or groups in all areas of interest to mitigate bias.

Growth in the global demand for traditional energy sources, coupled with growing concerns about the environmental impact of fossil-based fuels, has caused virtually all developed nations to prioritize energy-related issues. Related pulls in emerging markets derive from other natural resource issues. Potable water is a critical example, as many nations have either contaminated supplies or not enough water to support growing demands. Aging populations and the growing cost of health care have combined to focus attention on technologies related to health care, and concerns related to the potential for the rapid global spread of infectious disease add a new dimension to the need for health care solutions.

Societal Trends

The committee believes that a persistent forecasting system should monitor trends in society. Such trends may signal the emergence of critical challenges and problems, changes in the public policies that regulate R&D, changes in major global R&D initiatives, shifts of human and financial resources for scientific research and technical applications, changes in national and global priorities, and shifts in public opinion and social acceptance (or rejection) of technologies and applications. Interactions between agents (humans) in a complex system either amplify or dampen changes in perceptions or behaviors that can accelerate potential disruptive events. For example, the speed and type of disruptions in human biological engineering will likely be dictated by societal acceptability and ethical considerations. Over the past decade, technologies have been developed that monitor public sentiment surrounding brands and topics on the Internet. Using automatic sentiment analysis of text (also known as "buzz" detection) the system can monitor social networks and other online forums to detect changes in societal perceptions of innovative technology.

Societal attitudes can have a profound impact on the shape of the future. Examples include attitudes on nuclear weapons after the advent of the atomic bomb, the use of birth control, the ability to clone, the rise of online social networks, and the discovery of global warming. Societal reaction and cultural acceptability can have on irrevocable impact on future outcomes.

It is important to monitor trends in multiple segments of society, including business (both economics and finance), politics, and the arts.

Business Monetary flow is an important leading indicator of future trends in technology. In particular, venture capital, corporate R&D, university research, and government-sponsored R&D are of prime interest. The funding of the ARPANET by the Advanced Research Projects Agency of the Department of Defense was an example of an important signal. More recently, the size and growth in funding for alternative energy and clean technologies is a leading indicator of future potential breakthroughs. Signals in business can be monitored from both the supply and demand perspectives (see the next section, "Enablers, Inhibitors, and Precursors to Disruption").

Politics A nation's ability to marshal its capital and talent to drive change must be considered when forecasting future disruptive technologies. For example, the announced goal by the U.S. president in 1963 to land a man on the moon by the end of that decade (see Figure 5-3) caused resources to be allocated to key technological breakthroughs at the expense of other programs. Shifts in government policies, as well as the policies of nonstate actors such as the Organization of the Petroleum Exporting Countries, can impact the probabilities of disruptive technology events occurring within particular domains.

Copyright National Academy of Sciences. All rights reserved.

FIGURE 5-3 President John F. Kennedy's May 25, 1961, speech before a joint session of the Congress, in Washington, D.C.: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish."

Governmental policy can either impede or enhance a nation's innate S&T advantages. S&T policies play a crucial role in national strategy as well as in establishing and maintaining global competitiveness. National policies should synchronize future capabilities with S&T resources and R&D activities. Understanding the policies and tracking changes in them and in R&D activities may signal important changes in a nation's S&T priorities, attitudes, and concerns. These signals may be important signposts to track in a persistent long-term forecasting system.

Arts and Literature Because artists and writers are often on the leading edge of social change, it is important to keep up with the topics they are pursuing. Some places to look for an emerging norm might include the social causes found in musical lyrics, technologies described in science fiction, and warnings and dissent found in nonfiction. Societal resistance or polarity reflected in works of art may be indicative of technologies that have high disruptive potential. The persistent forecasting system can utilize contemporary tools to monitor a rich and diverse set of sources such as buzz logs for hot topics, changes in musical lyrics, new topics covered in the press, emerging concepts found in digitized books and periodicals, new postings on crowd-sourced sites like Wikipedia, tag clouds to identify new topics or relationships, and online social networks that uncover original social causes or important trends. Nevertheless, to mitigate bias, it will be important to reach beyond the Internet and digitized sources to include offline sources of information and information from underdeveloped and emerging countries as well as countries that have limited Internet connectivity.

Technology Sectors to Watch

For a technology to be considered disruptive there must be an application that can derive value from that technology. Potentially disruptive or not, technologies created in the absence of an application will have a difficult time being adopted. New applications of technologies could disrupt many sectors—health care, energy, materials,

Copyright National Academy of Sciences. All rights reserved.

communications, information technology, entertainment, defense, and transportation. Examples of potentially disruptive technologies and application sectors include these:

- Picture Archiving Communications Systems (PACS) and IT Systems (health care),
- Energy storage materials (energy/materials),
- Ubiquitous broadband wireless (communications),
- Cloud computing (information technology),
- Virtual reality and virtual goods (entertainment),
- Autonomous combat vehicles (defense), and
- New biobased fuels and technologies (transportation).

In general, the technology sectors most likely to yield disruptive advances are those that attract broad interest throughout the R&D community in both the public and private sectors. However, it is important to also examine the potential for disruption from crossover advances, where breakthroughs in one sector could spawn a diverse spectrum of advances in one or more other sectors.

Application Paths to Consider

Roadmapping is a time-honored technique for forecasting technological advances. However, it is most useful for forecasting raw technical capabilities rather than the applications enabled by technologies (Anders, 2008). For the latter, the solution pull dimension is of vital importance.

In assessing application paths it is instructive to work the problem from both ends. Technology roadmaps that forecast raw capabilities are useful in projecting the anticipated maturation path(s) for a given technology based on a particular set of assumptions. Another use of roadmapping is to highlight the impediments that require a fundamental breakthrough to proceed further along a given path. Linking roadmaps to the solution domain is, however, quite complex. In light of market demand, technologies that might be integrated to satisfy the solution pull and factors that currently limit solutions must be identified.

Whether working from the technology push or the solution pull perspective, identification of application pathways is difficult. With technology push, it is impossible to envision all potential applications of a given technology across all conceivable market domains. Similarly, from a solution pull perspective, it is not feasible to identify all possible building blocks, some of which may be nonmaterial, that could address a given market demand. Thus, the potential for disruption or surprise always exists, although it can be mitigated by using scenarios and red teaming (adversarial perspective) techniques, which seek to identify both novel applications of an existing technology and novel solutions to a perceived market demand. Backcasting (Chapter 2) is particularly suited to the task of exploring solution pull. It is not necessary to have perfect vision in order to have a relatively comprehensive inventory of potential building blocks for an envisioned solution. As long as these building blocks are frequently updated, the potential for surprise can be reduced. With backcasting, once the specific solution is envisioned the surprise is more likely to be a result of timing rather than a failure to anticipate the use of a particular building block.

Enablers, Inhibitors, and Precursors of Disruption

The greater the lead time gained by identifying key signals and signposts, the greater the ability of decision makers to prepare for future technological disruptions. A persistent forecasting system should consist of an aggressive, systematic, and ongoing effort to identify the enablers, inhibitors, and other precursors of potential technological disruptions using forecasting techniques like backcasting. Some examples of early warning sensors are supply factors, demand factors, price/performance ratios, adoption rates, and changes in historical relationships, correlations, or linkages. System operators should also consider social network analysis software, genetic mapping software, and supply chain software as tools for discovering and mapping complex systems.

Copyright National Academy of Sciences. All rights reserved.

Supply Indicators of Potential Disruptions

Once a potentially disruptive technology has been identified, the key supply chain factors that might enable or inhibit its manifestation should be identified. Some of these key factors could include the following:

- Requirement of raw materials and how much they cost,
- Raw material availability and stability of the supply—for example, if they are located in a country or area subject to natural disaster or political unrest,
- The cost of production, including costs for tooling and set-up for initial production,
- Performance requirements,
- Expertise and competence of the workforce,
- Quality of the infrastructure,
- Ancillary technologies required to produce enough to meet demand (scale),
- Any laws of nature that might stand in the way of a technological disruption, and
- Alternative approaches and techniques that would achieve the same outcome.

Once these factors are determined, the persistent forecasting system should be able to establish information-monitoring sensors as well as in-person information-gathering techniques to benchmark the progress toward disruption. Some factors, such as raw material or commodity prices, should be easy to monitor, while proxies or qualitative factors may be required in cases where information is not readily available.

Demand Factors in Potential Disruptions

Identifying demand factors (units, prices, etc.) that might cause a disruption is somewhat more challenging but not impossible. For instance, how much would an individual pay to live 50 years longer while maintaining the mental and physical characteristics of a young adult? What would a nation-state pay for a technology that could prevent or cure radiation sickness? Once a disruptive product or service can be imagined by one or another technique, the persistent forecasting system should consider key demand factors such as the following:

- Price elasticity of demand,
- Sources of demand,
- Estimated rate of diffusion,
- Cost of distribution, and
- Environmental, political, and national security issues and social demands and constraints.

Demand factors affect not only market-driven technologies and applications but also defense technologies. The production of F-22 fighter aircraft was halted when it was realized that high price and export restrictions would constrain the diffusion rate. The ongoing F-35 aircraft program, on the other hand, exemplifies less constraint on diffusion because of expansive demand factors due to lower prices and greater demand because the plane was developed specifically for export.

Once these factors have been determined, the persistent forecasting system should once again establish information-monitoring sensors as well as in-person information-gathering techniques to further benchmark progress toward disruption. Like supply factors, some demand factors should be relatively available while others, where information is less readily available, are likely to require a surrogate variable.

Signal Detection Methods

Signals can be detected using automated, computer-assisted, and manual methods. Computers can mine targeted databases and data feeds for changes in the measurements of interest and identify those measurements that might exceed preset threshold values. These values are set by forecasters using Chapter 2 forecasting methodologies such as trend analysis, causal modeling, and road mapping; signposts and tipping point values can also

Copyright National Academy of Sciences. All rights reserved.

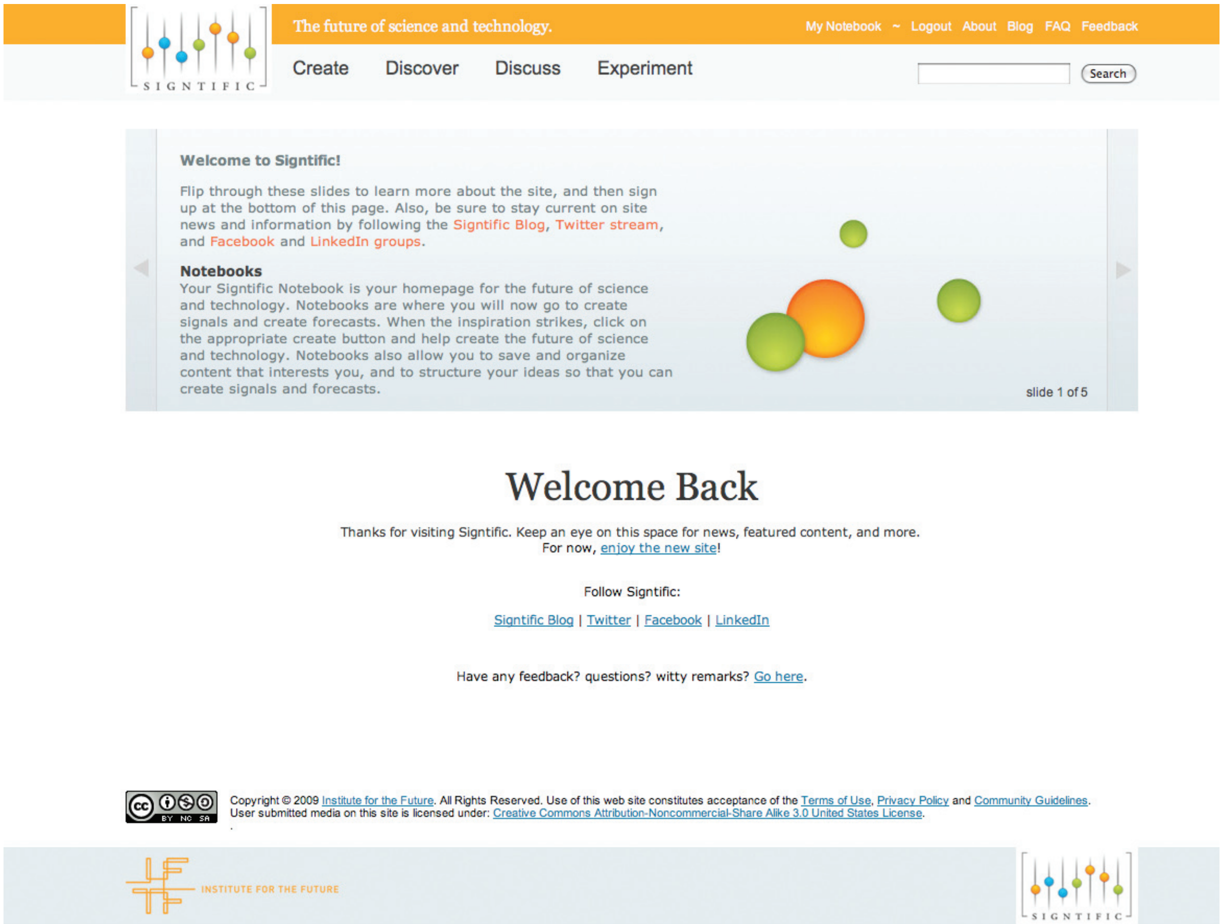


FIGURE 5-4 Signtific screen, available at http://www.signtific.org/. SOURCE: Courtesy of the Institute for the Future.

be extracted from previous forecasting exercises and processes. Operators of the forecasting system can predefine which databases and data feeds may be of interest. Once targeted, programs can be written to extract the signals of interest using data analysis software and tools.

Computer systems can be programmed to automatically monitor Web sites, posted papers, and blogs to extract potential signals. Word spotting, standing queries matching, topic clustering, resource description framework (RDF) topic mapping,[45] sentiment analysis, and threshold monitoring are approaches that can be used by automated systems to extract signals from unstructured data sources.

Signals can also be detected manually through expert or crowd curation.[46] Forecasting systems such as Signtific ask experts to identify and input signals of interest to be shared and analyzed by other experts (see Figure 5-4).

[45]"Topic maps are designed to facilitate the organization and navigation of large information collections through the use of an open (non-controlled) vocabulary using topics, associations, and occurrences. A topic may represent any concept, including subject, person, place, organization, and event. Associations represent the relationships between those concepts; and occurrences represent relevant information resources. Although sometimes used when referring to an ontology, taxonomy, or thesaurus, a topic may, in fact, incorporate any combination of these. Available at http://www.quantum3.co.za/CI%20Glossary.htm. Accessed on July 16, 2009.

[46]Digital curation is the selection, preservation, maintenance, and collection and archiving of digital assets. Available at http://en.wikipedia.org/wiki/Digital_curation. Accessed on August 7, 2009.

Copyright National Academy of Sciences. All rights reserved.

FIGURE 5-5 TechCast screen, available at http://www.techcast.org/. SOURCE: Courtesy of http://www.techcast.org.

TechCast uses an approach in which an administrator poses a question or proposes a forecast and solicits inputs from experts that can be used to generate signals (see Figure 5-5). Experts can also use prediction markets to generate signals. Similar signal curation approaches can be used with crowds.

Computer-assisted approaches combine the power of computers to mine and search rich sources of information (such as the Web, databases, and data feeds) and the power of humans to make judgments, identify patterns, and use intuition. Analysts and forecasters can use search engines, alerting systems, visualization tools, and computer models to generate signals. Humans can also play out various future scenarios using simulations and gaming technologies run on computers. Signals can be extracted from the results of these simulations and games.

Exception and Anomaly Processing Tools

While data analysis is an old and established field of study, many analytical tools are best applied in noncomplex systems that have common similar data structures and content. Traditional statistical methods such as time-series analysis and exploratory data analysis can be applied to forecasting in noncomplex systems. Data

Copyright National Academy of Sciences. All rights reserved.

analytic techniques for finding complex patterns, weak signals in noisy environments, or nonbinary correlations are less established than techniques used in noncomplex systems. However, with the advent of the Internet and greater processing power, significant progress has been made, and there are several analytical techniques that show promise for identifying potential disruptions in complex environments. Which tools are best? As discussed earlier, Vanston (2003) argued that

> the real challenge is not to determine which [approach] is the right one, or even which is best; the challenge is to use these different approaches in concert to develop sound, credible, comprehensive forecasts.

Chapter 2 of this report identified and discussed several traditional approaches for reducing available data into a form that can provide a meaningful input to the generation of a forecast. In general, with the exception of some of the gaming and simulation techniques, these methodologies rely on readily discernable patterns in historical data. The following subsections, by contrast, highlight several classes of tools that are well suited to identification of the more obscure patterns and signals believed to be critical to the success of the persistent forecasting system. Note that the list is not meant to be comprehensive, nor is it meant to be prescriptive for a specific technique.

Vision-Widening Tools for Complex Systems

With the advent of the Internet, we have seen rapid growth in social networks, online gaming, virtual worlds, and other proxies that closely approximate complex systems. The persistent forecasting system should, accordingly, consider using proxies of complex adaptive systems (CASs) to identify potential future outcomes, identify new signals of changes in societal trends, and monitor the rate and breadth of their diffusion. These CAS proxies include, but are not limited to, virtual worlds, alternate reality games (ARGs), massive multiplayer online role-playing games (MMORPGs), and online social networks. Further, the diversity (thousands of player types) and magnitude (millions of participants) of these environments suggests that insights can be gained on how different societies might respond under the stress of different force changes. Another novel approach that could be explored is the use of crowd sourcing for analysis by making data sets collected in virtual worlds public.

Finally, system operators should consider utilizing storage technology tools such as snapshotting. One of the challenges of CASs, including the online proxies mentioned here, is that they are irreversible; this makes testing alternate realities a challenge. It should, however, still be possible to gain experience in potential alternate outcomes by using other tools. For example, the persistent forecasting system might consider using state-of-the-art enterprise storage technology to take snapshots of the states of the online systems at various points in their simulation time line. The system operators could then consider injecting those snapshots into massive scenario generators, manipulating key force variables (natural disaster, economic hardship, etc.) to extreme conditions, and observing how the system changes under different conditions. It may also be useful to create alternate online worlds or games with similar starting points but different economic, legal, or environmental conditions. These novel approaches should be considered in conjunction with more established techniques of future gazing such as traditional scenario analysis.

Morphological analysis and agent-based models are other data organization techniques that should be considered.

Simulation

While it is difficult, if not impossible, to forecast the timing of external shocks, decision makers can still benefit from simulating their impacts and alternative future outcomes under different conditions. The insights gained from running these simulations can be used to modulate the impact of surprise through better allocation of resources.

The stakeholders of the persistent forecasting system can rank existing and new potential investments by testing how their resource allocation and portfolio choices hold up when extreme visions of the future are simulated. Consideration can be given to systematically moving key variables to extreme conditions and injecting random

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

high-impact events into various types of CAS models (such as in virtual worlds, ARGs, MMORPGs, online social networks, or approaches using techniques to generate mass scenarios).

For instance, it might be useful to create existing models of the physical world (or use existing ones) and systematically test various futures, injecting random high-impact events such as economic calamity, sudden resource scarcity, natural disasters, war and conflict, or a scientific breakthrough. From this exercise, the stakeholders should be able to identify key tipping points, system fragilities, unrecognized linkages, critical interdependencies, or resource scarcities that may signal areas of technological obsolescence or increased pressure for technological innovation. It is imperative that stakeholders analyze the potential scope of disruptions and put in place a portfolio of investments in advance of a potential event so that if the event does occur, stakeholders are able to increase the number of alternative reactions and outcomes. Using this approach, decision makers will likely be better prepared to mitigate the effects of surprise with proper planning and resource allocation.

Text Mining

With almost 80 percent of global information stored in unstructured text (see the discussion on processing unstructured data), mastery of text mining will be a critical enabler for a persistent forecasting method that reduces the probability of unlikely events.[47] Without text mining, it would be extremely difficult and expensive to organize, structure, and load RDBs and RDFs. Text mining opens up the potential for harvesting information from the Web on a massive scale and structuring the data for analysis. The disciplined, continuous scanning required to enable a persistent forecasting effort is made feasible by text mining systems. Fortunately, such efforts are not novel, with the United Kingdom having gone so far as to establish the National Center for Text Mining (NaCTeM).[48]

Data Relevancy Testing

One method of preventing information overload is the application of relevancy tests. Presenting only data that could lead to impactful disruptive events would be an obvious way of managing information load. This suggests that when a potential disruptive future event is identified, system operators will need to utilize backcasting techniques to identify enablers, inhibitors, and force drivers. Once identified, data feeds could be monitored for each of these factors, with information presented to the user only when certain threshold levels are hit.

Storing Queries

Pioneered by Jeff Jonas (2006) as part of work first done to help understand cases of fraud in Las Vegas casinos, Non-Obvious Relationship Awareness (NORA) uses protocols similar to RDF analysis; however, it is dependent on a well-characterized initial question set, which is then used to count events or activities and then determine the likelihood that they are related. Specifically, this system allows queries to be stored as part of the data set and remain active for the life of the database. This creates an opportunity for the data and the query to coincide and signal the event to an end user. In effect, the query is acting like an agent receiving confirming or disconfirming feedback.

Pattern Recognition Tools

Pattern recognition tools are also critical to finding early weak signals in complex data sets. With appropriate visualization tools, human analysts are capable of picking up some patterns in large, complex sets of data. Augmenting human analysis with computer pattern recognition can greatly enhance pattern recognition performance, especially in large dynamic data sets. The field of pattern recognition is well established. Specialized pattern recognition tools and techniques will need to be developed over time, particularly as new disruptions occur. As part of the review and assessment phase, the persistent forecasters will need to develop pattern learning sets in their

---

[47]Available at http://en.wikipedia.org/wiki/Intelligent_text_analysis. Last accessed October 23, 2008.
[48]Available at http://www.ariadne.ac.uk/issue42/ananiadou/. Last accessed October 24, 2008.

Copyright National Academy of Sciences. All rights reserved.

priority areas of focus. The International Association for Pattern Recognition would be a good place to start for identifying cutting-edge and relevant techniques that might be applicable for disruptive technologies.[49]

Link Analysis Tools

Link analysis and monitoring are powerful tools for identifying signals of a potential pending disruption. Rapid variations in the rate of change of the strength, frequency, or number of linkages relative to the historical baseline or the status quo can serve as a tangible warning that the likelihood of a disruption is increasing. This requires that the persistent forecasting system establish baseline data for key areas of focus and the driving forces described earlier. Unforeseen or underappreciated (from a risk standpoint) linkages, interdependencies, and self-organizing factors manifest themselves when the dynamics of a key driver changes. This is the hallmark of a complex adaptive system (CAS).

The persistent forecasting system operators should consider including a baseline of historical reference data in priority areas and robust link analysis tools to identify changes in linkages, including the establishment of new links, the breakage of established links, and changes in the strength or number of links.

Using link and visualization tools like those used by the Visual Thesaurus, one can imagine the relationship between words and terms[50] and other entities. These tools are also used to visualize social and information networks. Many link analysis tools are well established and available commercially.

OUTPUTS AND ANALYSIS

Identifying the appropriate tools and creating the right processes and engines by which information is analyzed are only the first steps to ensuring the success of a persistent forecasting system. The information must also be presented in a clear and consistent manner to facilitate analysis. The analysis is typically facilitated via a range of visualization tools that provide alternative dynamic representations of the processed data. Visualization tools help humans to be more efficient and effective in recognizing patterns in massive data sets. The operators of the persistent forecasting system should incorporate a robust set of visualization tools.

Signal Evaluation and Escalation

In a signal escalation process, the forecasting system uses methods that allow signals to be analyzed individually by both experts and the crowd. An expert looks at a signal and concludes the analysis by recommending that the signal be either ignored or escalated. Individual expert analyses and recommendations should then be collected and posted in public for all to see. Creating an ongoing conversation among experts and a crowd with multiple viewpoints should be one of the goals of a persistent forecasting system, with the aim of stimulating still further feedback and analysis.

A signal should be escalated even if only a single expert recommends it—that is, escalation should *not* depend on consensus. To deter consensus interpretation of signals, experts from different disciplines should be encouraged to review signals separately. The expert(s) recommending escalated analysis should also suggest the appropriate escalation type. For example, should another expert with expertise in another discipline review the data? Should the signal be placed into a virtual world, a role-playing game, or some other method of testing and learning? Does the signal spur more questions? In this last case, such questions should be input into the system as a persistent query.

Visualization

Forecasts provide important data on potential futures to decision makers and stakeholders but must be represented in a clear and informative way in order to be useful. Computers organize and represent data in a vastly different way than human beings: Representations suitable for a computer algorithm are often not suitable for

[49]More information available at http://www.iapr.org/. Last accessed August 24, 2009.
[50]Available at www.visualthesaurus.com. Last accessed October 24, 2008.

Copyright National Academy of Sciences. All rights reserved.

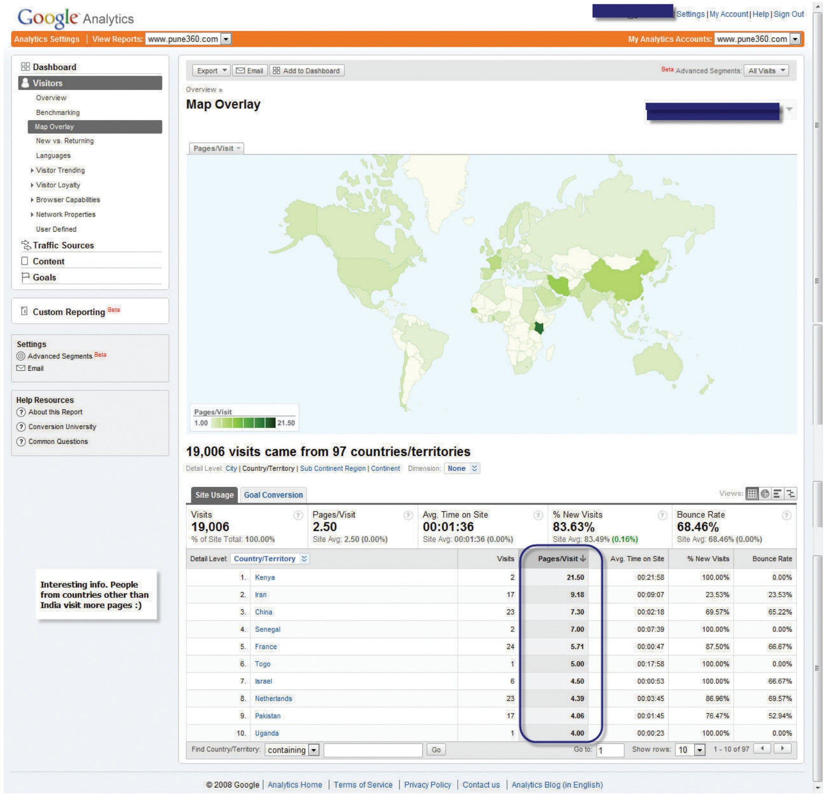


FIGURE 5-6 Example of a heat map. SOURCE: Google Analytics.

humans and vice versa. If a decision maker cannot understand a model or the solution produced by an algorithm, then the algorithm, model, and solutions are effectively useless.[51]

The human mind can quickly process complex information received visually. Computer-generated visual representations and interaction technologies provide the tools for users to see and interact with large volumes of information at once. Visual analytics build on this ability to facilitate the analytical reasoning process (Thomas and Cook, 2005).

With forecasting methodologies such as trend analysis, TRIZ, influence diagrams, and prediction markets, visualization tools can produce a graphical model of the progression (both past and potential future) of technology and the factors that might have a direct effect on the development, adoption, and applications of technology.

Existing Visualization Tools

There are well-known methods of charting, graphing, and presenting information that have been successful for decades. Pie charts, bar graphs, and scatter plots are the standard output of Microsoft Excel, Google spreadsheets, statistical analysis software (SAS), and Mathematica. However, with the dramatic increases in computing power over the past 50 years, there are many new ways to visualize information. Maps, long one of the richest methods for visualizing data, may now be combined with data sets in a number of novel and visually empowering manners. Heat maps, like those used by Google Analytics and SmartMoney, are popular examples of visualizing clusters of related data (see Figure 5-6). Other graphics tools such as geo mashups, link diagrams, transaction maps, and

[51]Christopher Jones, *Visualization and Optimization,* Bellingham, Wash.: Kluwer Academic Publishers, 1996, p. 3.

Copyright National Academy of Sciences. All rights reserved.

time-line plots are widely used by analysts for investigatory analytics. Graphs of network nodes, subways, gene paths, page views, and other data-intense subject matter have pushed the boundaries of visualization and shown great potential for expansion into new areas.[52]

Ideal Visualization Dashboard

Dashboards are executive information systems that present data in summary formats. They leverage visual analytics and intuitive user interface designs to produce interactive and easy-to-read overviews of complex data holdings. It is believed that the ideal dashboard will have several key visualization and analytical attributes.

- *Handle large amounts of data***.** Visualization tools must allow the users to evaluate mass quantities of data or granular data quickly and with equal ease. For example, it might be useful to have a heat map that allows the user to look at the entire universe of data at a glance to identify outliers or concentrations of activity. This capability should be combined with interactive tools that allow the user to further investigate specific data points of interest. Some examples of such capabilities are HealthMap,[53] which monitors disease alerts on a global map, and FINVIZ,[54] a financial visualization site designed to support stock traders that monitors stock market activity overlaid on a heat map.
- *Vary timescales.* The dashboard should have capabilities that allow users to manipulate or change views on a variety of different timescales. Changes that might be missed in the shortterm might become more obvious on a longer timescale.
- *Use global representations.* The dashboard should visually represent to the users potential disruptive activities occurring throughout the world. Data sets and real-time data feeds can be combined[55] with maps to provide geocontext for the data. This is especially important given the relationship of disruptive technologies to techno clusters.[56] The dashboard should use geospatial visualizations like those developed by Google Earth and the Environment Remote Sensing Institute (ERSI).
- *Macro- and user-defined alerts.* The dashboard should also have alerts that are both macro- and user-defined. For example, FINVIZ generates tables that show the performance of macromarket indicators as well as stocks that are performing at the extremes or that have hit certain threshold signals (see Figure 5-7). Macromarket indicators include total advancing/declining stocks, total new highs/new lows, and total stocks above/below the moving average. FINVIZ also has tables that show stocks that have tripped widely monitored threshold triggers such as unusual volume activity, most volatile, overbought, oversold, top gainers, top losers, stocks hitting new highs or new lows, stocks with large numbers of insider transactions, and stocks with upcoming earnings announcements. The FINVIZ site also includes several technical default thresholds such as stocks hitting trendline support or trendline resistance and stocks that are in an up channel or a down channel. These are all examples of indicators that are of interest to particular types of financial advisors. A similar system could be built for forecasters to track signals and signposts of potentially disruptive technologies.
- *Allow for search and real-time filtering.* The dashboard should include tools for search, filtering, alerting, and analytics. Some examples might include (1) keyword search, (2) filtering based on user-defined variables, and (3) user-defined analytics to recognize changes in relationships between variables.

[52] An excellent discussion of data visualization can be found at the Many Eyes site, which is part of IBM's Collaborative User Experience Group. Available at http://services.alphaworks.ibm.com/manyeyes/home. Last accessed May 6, 2009.

[53] Available at http://healthmap.org/en. Accessed on August 7, 2009.

[54] Available at http://finviz.com/. Accessed on August 7, 2009.

[55] A mashup is a Web application that combines data or functionality from one or more sources into a single integrated application. More information available at http://en.wikipedia.org/wiki/Mashup_(web_application_hybrid). Last accessed May 6, 2009.

[56] A techno cluster is a high-technology-oriented geographic concentration of interconnected technology businesses, suppliers, universities, and associated institutions. More information available at http://en.wikipedia.org/wiki/Business_cluster. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

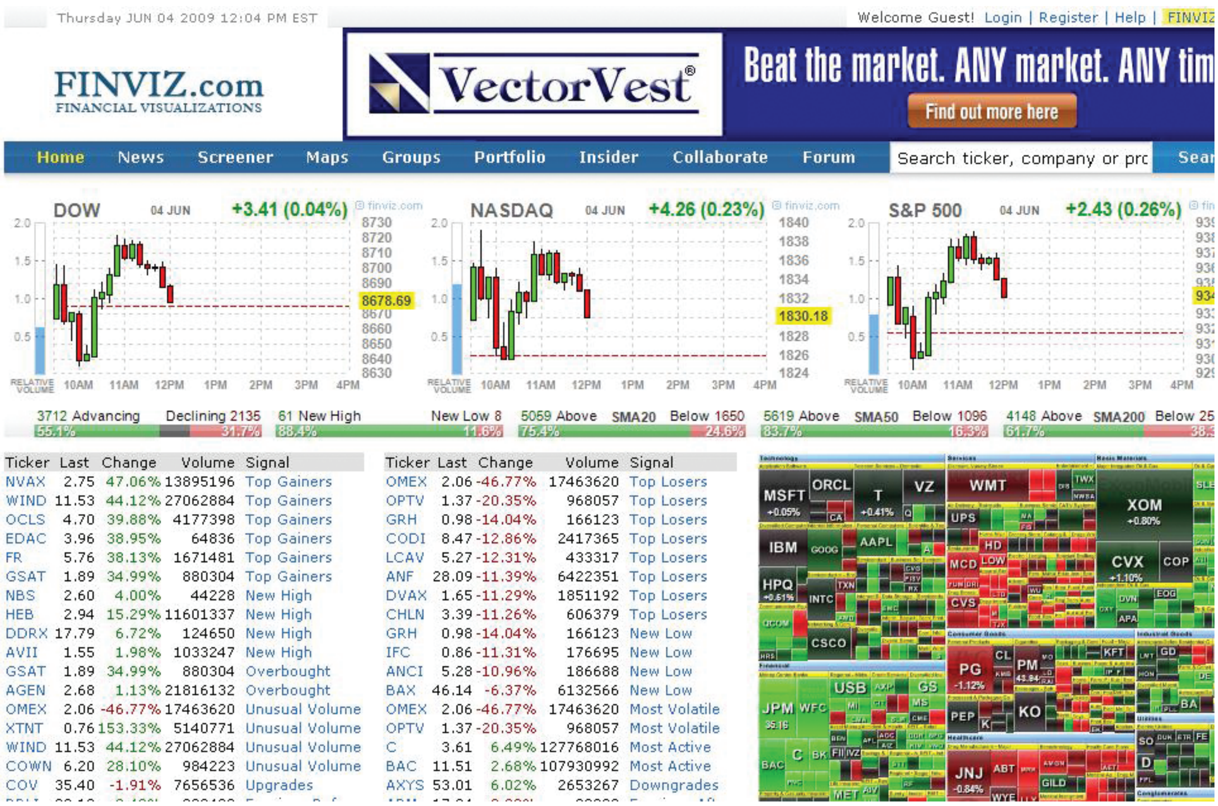


FIGURE 5-7 Finviz.com dashboard. SOURCE: Courtesy of FINVIZ.com, Financial Visualizations.

- *Support user communities.* The dashboard should have tools that allow for the formation of user communities and provide tools to capture and monitor signals of interest from these communities.

An ideal persistent disruptive technology forecasting system might include global maps showing patent filings, venture capital investments, natural disasters, raw materials supply chains, and political stability. These indicators might be color-coded to show improving/deteriorating conditions in each of the major indicators. Indicator-specific dials would allow the user to drill down into subjects of interest, especially outliers. For instance, if an earthquake occurs near the mine in Chile that supplies a significant portion of the globe's lithium needs, natural disaster and key raw materials triggers might be jointly tripped that would flash as a hot spot on a global map (see Figure 5-8). The end user would then drill down at the hot spot, where the earthquake and raw material data would be in a state of deterioration. Drilling down another level would reveal companies, technologies, and products that could be adversely impacted by the event and also reveal alternative sources of supply. Chronological dials could be moved backward and forward in time to see how much lithium material is available in the supply chain and how it has changed over time in order to assess how long it will take for the shortage of lithium to impact end users.

The dashboard should also include tables showing thresholds that have been recently triggered. An example might include using a tag cloud (see Figure 5-9) or a link diagram to track the appearance of a new word from an established research domain in a scientific journal or paper, or a list of new links in an online social network, suggesting that relevant experts/analysts evaluate the meaning of the trigger.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

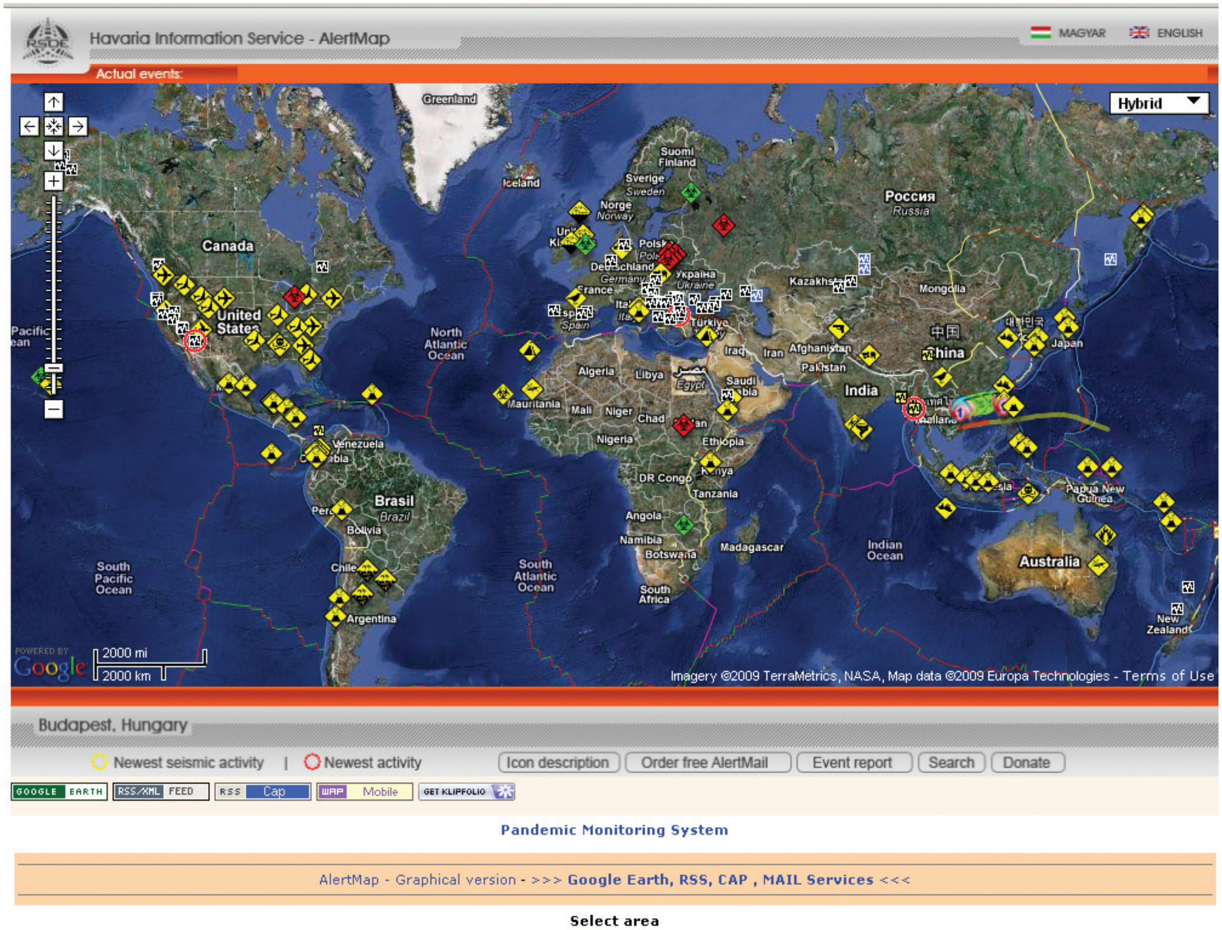


FIGURE 5-8 Screenshot of Havaria Information Services AlertMap. SOURCE: Courtesy of RSOE, http://visz.rsoe.hu/alertmap/index2.php.

FIGURE 5-9 Tag cloud generated for the scientific revolution using the Many Eyes Beta Site for Shared Visualization and Discovery by IBM. SOURCE: Courtesy of Many Eyes. More information available at http://manyeyes.alphaworks.ibm.com/manyeyes/page/Tag_Cloud.html.

Copyright National Academy of Sciences. All rights reserved.

POSTPROCESSING AND SYSTEM MANAGEMENT CONSIDERATIONS

Review and Reassess

Building the ideal persistent forecasting system will be an iterative process that may take years to mature. The committee believes the best way to improve the system over time is to systematically conduct internal and external reviews of processes, tools, and personnel. A persistent forecasting system comprises a combination of technology, processes, and people. While this report focuses on the technology, it is just as important to consider the other two components when creating a persistent forecast. These reviews should be conducted on a regular basis, at least annually.

Internal and external reviews should be done separately and by rotating personnel. The forecasting system should also have a robust set of tools for receiving feedback from the general public and from internal staff and experts. When a disruption does occur, whether predicted or not, the operators of the persistent forecasting system should consider backtesting to see if it could have been detected earlier with different techniques or personnel.

Expert Interpretation of Automatic Output

It is important to note that while computer modeling, systems, and heuristics have grown increasingly sophisticated they still lack the ability to assert insights. Computers are extremely efficient and effective at performing calculations, analyzing, and finding basic patterns. Search engines and databases are capable of analyzing hundreds of millions of pages of information per second. They are perfect for performing extremely high-speed repetitive operations, but for all of their speed they are still not able to mimic the performance of the human mind for understanding complex associations and patterns.

The human mind is remarkably skilled at finding solutions through intuition and sophisticated questioning. This ability of humans to understand patterns and problems without previous experience or empirical knowledge separates humans from computers.

Computer analytical and alerting systems are powerful tools that can be programmed using human rules to analyze large data sets. They can search the Internet for specific patterns, generating dashboards of information for human analysis. That information can be harnessed by the user through the Web to extract the wisdom of crowds (Surowiecki, 2004) through crowd sourcing and expert-sourcing. The idea behind creating an open, persistent forecasting system is to bring together the power of computer networks and the wisdom of human networks.

Backtesting

Looking back from 2009, it is easy to see what some of the most important technological themes over the past 30 years have been: ubiquitous communications (Internet, cell phones, wireless devices) and pervasive computing (PCs, cloud computing, server farms), digitization (iPods, DVDs, digital books), globalization of the supply chain (information technology, overnight transport), stealth (military applications), energy efficiency (automobiles, low-energy appliances, computing), clean energy (wind and solar) , bioengineering (genetic research, pharmaceuticals, regenerative medicine), and micro- and nanoscale manipulation (MEMs, nanomaterials). In 1979, would those same themes have been so easily anticipated? How would previous forecasts have identified these themes and their disruptive impact?

Venturing further back in history to 1905, one could witness the battle between two rival technologies to power the world's automobiles. In 1906, a steam-powered vehicle set the land speed record, reaching 127 miles per hour (see Figure 5-10). Steam-driven vehicles were quieter, and their underlying technology was more widely known, allowing for easier service (Pool, 1997). However, steam was not to win. At that time, the gasoline engine was just an emerging technology, but the increasing facility in drilling for petrochemicals and the advent of mass production techniques would create one of the most disruptive technologies of the twentieth century. Why did forecasters at that time not see how important this battle was and the long-term technology impact of the gasoline engine?

Backtesting the forecast methods employed by the system over time is important, and comparing past forecasts to their actual outcomes will be a critical aspect of learning from these efforts and refining the system. Backtest-

Copyright National Academy of Sciences. All rights reserved.

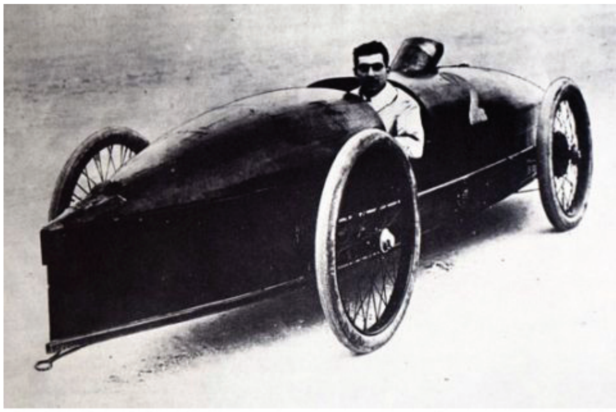


FIGURE 5-10 Stanley Steamer Rocket setting the land speed record in 1906 of 127.659 mph. SOURCE: Available at http://patentpending.blogs.com/patent_pending_blog/images/stanley_steamer.jpg.

ing is a good way of evaluating the effectiveness and efficiency of forecasting tools and the quality of collection sources.

System Management

The persistent forecasting system operators and their infrastructure must also meet a minimum set of characteristics, detailed below.

Financial Support Strategies

The fact that the system is persistent suggests that long-term financial support and sustainability are critical requirement and that the system cannot be cost-prohibitive to either create or sustain. In general, the allowable cost should be proportional to the perceived economic benefit of a forecasting system that would lead to improved decision making.

A number of strategies can be used to finance persistent systems. One strategy is to have one or more sponsors commit to an ongoing sponsorship of the system. Typically, there are anchor sponsors that make a long-term financial commitment. These sponsors can be government agencies from one or more governments, corporations, foundations, academic institutions, or nonprofit organizations. Another approach is to incorporate the activity into an internal organization that provides funding. A third approach is to build an organization (either for profit or not for profit) for the exclusive purpose of operating the system as a stand-alone enterprise. The organization could be funded by revenues from selling forecasting services and publishing forecasts, direct donations, or by foundational or governmental support.

Secure System Infrastructure

The persistent forecasting system requires an infrastructure robust enough to protect data against outages, malicious attack, or intentional manipulation. This is especially true for a persistent forecasting system that has been designed for global collaboration. The data system should support the ability to be parsed and analyzed across multiple quantitative and qualitative vectors simultaneously, without compromising the underlying raw data. The technology infrastructure needs to be highly scalable to support a large user base with an adequate amount of bandwidth and processing power so as not to discourage active and ongoing participation. Additionally, a robust back-up and recovery architecture must be in place.

Copyright National Academy of Sciences. All rights reserved.

Because persistent forecasting systems will likely contain many complex data sets, the data structure must be dynamic and scalable. The underlying infrastructure (storage, processing, networking, and power) must be designed for speed, capacity, and redundancy. Commercial examples of such infrastructures include Google's BigTable and Amazon's SimpleDB.[57]

Information Integrity

The persistent forecasting system must be free from manipulation. Maintaining robust auditing and monitoring tools is an important feature of a trusted forecasting system. Furthermore, it should gather, process, and disseminate information in as close to real time as possible. Certain simulations and other procedures may require advanced data management tools such as snapshotting[58] and cache coherency.

Data authenticity is itself an important topic. Data should not be discarded simply because it cannot be authenticated as genuine beyond repudiation. In fact, early signals of a potential pending disruption are often incongruous with the known order and therefore difficult to authenticate or corroborate. Therefore, the committee believes that although the ideal system should consider data authenticity, it should not require that data be authenticated.

Information integrity[59] and credibility are among the most important attributes of any forecasting system. Together they improve the legitimacy of the forecast and increase the confidence of decision makers in allocating resources.

Information integrity can be threatened by bias. Sourcing and assessing data from multiple perspectives (countries, languages, cultures, and disciplines) can significantly reduce the adverse impact of bias, as discussed in Chapter 4. Concealed manipulation of data can undermine information integrity, so that an ideal system should consider using a variety of techniques and algorithms to identify when, how, and why data have been changed to reduce undetected alteration. An immutable audit log should be built into the forecasting system to track the source and flow of all of the data and the forecast. It would be a tamper-resistant record of how a system has been used and would invite everything from when data arrives, changes, and departs, to how users interact with the system. Each event is recorded indelibly, and no one, including the database administrator with the highest level of system privileges, could alter the record. Immutable audit logs enable users to track information flows and analyze the way each prediction was made.[60] Because each prediction can be traced to its source, the creditability of a forecast can be established based the source of the data and how it was processed and interpreted.

To allow for an understanding of the timeliness, relevance, and legitimacy of data streams, information integrity processes should, at a minimum, do the following:

- Keep track of data characteristics, including time, source, format, geography of origin, and language;
- Measure accuracy of the data source;
- Determine source reliability (has the data contributed by the source been accurate in the past?) or measure confidence in the data (in addition to asking participants to make a prediction, ask them how confident they are in the prediction);
- Ascertain data availability (persistent, periodic, or one-time availability);
- Perform regular audits of the system;
- Determine if the data were altered; and
- Provide strong controls for privacy and rights management.

By tracking the global information characteristics of the data surrounding a potentially disruptive technology, forecasters can assess the maturity of the technology space (how frequently is the technology of interest discussed?),

[57]Available at http://labs.google.com/papers/bigtable.html and http://aws.amazon.com/simpledb/. Last accessed May 6, 2009.

[58]A snapshot is a copy of a set of files and directories as they were at a particular point in the past. Available at http://en.wikipedia.org/wiki/Snapshot_(computer_storage). Last accessed May 6, 2009.

[59]"Information integrity" is the trustworthiness and dependability of information. It is the accuracy, consistency, and reliability of the information content, processes, and systems. Available at http://www.infogix.com/information_integrity_defined. Last accessed July 17, 2009.

[60]Available at http://jeffjonas.typepad.com/jeff_jonas/2007/11/found-an-immuta.html. Last accessed, July 16, 2009.

Copyright National Academy of Sciences. All rights reserved.

the rate of diffusion (spread of "new mentions"), and the potential impact (breadth and depth of mentions—how many cultures, disciplines, and languages?).

Resource Allocation and Reporting

Once a potential disruptive technology has been identified, key decision makers will want an assessment of the likelihood of the disruption, its probable impact, factors that could accelerate the disruption, and factors that could inhibit it. Further, they will also want to know key interdependencies or fragilities in the set of events that could lead to a disruption. This information should provide the decision makers with the information that they require to allocate resources that will shape the impact of the disruption when it does occur. Further, decision makers will need to be periodically updated on the status of potential disruptions. Therefore, operators of the persistent forecasting system should create a disruptive technology assessment report for each new potential disruption identified, in addition to regular updates.

REFERENCES

Published

Anders, George. 2008. Predictions of the past. *The Wall Street Journal.* January 28. Available at http://online.wsj.com/article/SB120119993114813999.html. Accessed April 8, 2009.

Blainey, Geoffrey. 2002. *A Short History of the World*. Chicago, Ill.: Ivan R. Dee, Publisher.

Enis, C.R. 2005. Expert-novice judgments and new cue sets: Process versus outcome. *Journal of Economic Psychology* 16(4): 641-662.

Faber, Malte, Reiner Manstetten, and John Proops. 1992. Toward an open future: Ignorance, novelty, and evolution. Pp. 72-96 in *Ecosystem Health: New Goals for Environmental Management*, Costanza, Robert, Bryan G. Norton, and Benjamin D. Haskell, eds. Washington, D.C.: Island Press.

Greenfield, P.M. 1997. Culture as process: Empirical methodology for cultural psychology. In *Handbook of Cross-Cultural Psychology*, J.W. Berry, Y.H. Poortinga, and J. Pandey, eds., Boston, Mass.: Allyn and Bacon.

Günther, Isolda de Araujo. 1998. Contacting subjects: The untold story. *Culture and Psychology* 4(1): 65-74.

Gupta, Hari M., Jose R. Campanha, and Rosana A.G. Pesce. 2005. Power-law distributions for the citation index of scientific publications and scientists. *Brazilian Journal of Physics* 35(4A): 981-986.

Johnston, Rob. 2003. Reducing analytic error: Integrating methodologists into teams of substantive experts. *Studies in Intelligence* 47(1): 57-65. Available at https://www.cia.gov/library/center-for-the-study-of-intelligence/csi-publications/csi-studies/studies/vol47no1/article06.html. Last accessed May 8, 2009.

Jonas, Jeff. 2006. Enterprise intelligence: Conference proceedings from TTI/Vanguard. Available at http://jeffjonas.typepad.com/jeff_jonas/2007/03/enterprise_inte.html. Last accessed October 23, 2008.

Kennedy, John F. 1961. Special message to the Congress on urgent national needs. John F. Kennedy Presidential Library and Museum. Available at http://www.jfklibrary.org/Historical+Resources/Archives/Reference+Desk/Speeches/JFK/003POF03NationalNeeds05251961.htm. Last accessed on August 10, 2009.

Kuechler, M. 1998. The survey method: An indispensable tool for social science research everywhere? *American Behavioral Scientist* 42(2): 178-200.

Mandelbrot, B. 1963. The variation of certain speculative prices. *Journal of Business* 36: 394-419.

Önkal, D., J.F. Yates, C. Simga-Mugan, and S. Öztin. 2003. Professional vs. amateur judgment accuracy: The case of foreign exchange rates. *Organizational Behavior and Human Decision Processes* 91: 169-185.

Pareek, U., and T.V. Rao. 1980. Cross-cultural surveys and interviewing. In *Handbook of Cross-Cultural Psychology*, vol 2, H.C. Triandis and J.W. Berry, eds. Boston, Mass.: Allyn & Bacon.

Pool, Robert. 1997. *Beyond Engineering: How Society Shapes Technology*. New York: Oxford University Press.

Schwartz, Peter. 1991. *The Art of the Long View*. New York: Currency Doubleday.

Servan-Schreiber, Emile, Justin Wolfers, David M. Pennock, and Brian Galebach. 2004. Prediction markets: Does money matter? *Electronic Markets* 14(3): 243-251.

Shirkyon, Clay. 2008. Gin, television, and social surplus. Available at http://www.herecomeseverybody.org/2008/04/looking-for-the-mouse.html. Last accessed October 24, 2008.

Copyright National Academy of Sciences. All rights reserved.

Spann, Martin, and Bernd Skiera. 2003. Internet-based virtual stock markets for business forecasting. *Management Science* 49(10): 1310-1326.

Surowiecki, J. 2004. *The Wisdom of Crowds: Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies, and Nations*. New York: Random House, Inc.

Tauberer, Joshua. 2008. What is RDF and what is it good for? Available at http://www.rdfabout.com/intro/?section=contents. Last accessed October 23, 2008.

Thomas, J.J., and K.A. Cook. 2005. *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. Richland, Wash.: National Visualization and Analytics Center. Available at http://nvac.pnl.gov/agenda.stm. Last accessed May 8, 2009.

Triandis, Harry C. 1995. *Individualism and Collectivism*. Boulder, Colo.: Westview Press.

Triandis, Harry C., Peter Carnevale, Michele Gelfand, Christopher Robert, S. Arzu Wasti, Tahira Probst, Emiko S. Kashima, Thalia Dragonas, Darius Chan, Xiao Ping Chen, Uichol Kim, Carsten de Dreu, Evert Van de Vliert, Sumiko Iwao, Ken-Ichi Ohbuchi, and Paul Schmitz. 2001. Culture and deception in business negotiations: A multi-level analysis. *International Journal of Cross Cultural Management* 1(1): 73-90.

Vanston, John H. 2003. Better forecasts, better plans, better results. *Research Technology Management* 46(1): 47-58.

Weber, E., C. Hsee, and J. Sokolowska. 1998. What folklore tells us about risk and risk taking: Cross-cultural comparisons of American, German, and Chinese proverbs. *Organizational Behavior and Human Decision Processes* 75(2): 170-186.

Unpublished

V.S. Subrahmanian, 2008. “Scalable text mining.” Presentation to the committee on May 29, 2008.

Copyright National Academy of Sciences. All rights reserved.

6

Evaluating Existing Persistent Forecasting Systems

INTRODUCTION

The committee selected three existing forecasting systems with which to compare the committee's ideal system characteristics. Three criteria were considered for their selection. First, each of the systems attempted to forecast and track multiple technology arenas of interest to society at large (information technology, biotechnology, energy, and so on). Second, each system solicited the viewpoints of multiple experts, though the degree of openness to nonexperts varied. Third, the committee was able to access each system and meet at least once with a senior member of the staff. The Institute for the Future's (IFTF's) X2 system was chosen at the sponsor's request. The remaining two systems, Delta Scan and TechCast, were chosen because they facilitated evaluation of different approaches to forecasting, presentation of the data, persistence, and openness to the public.

Each of the three selected systems is described next, along with its strengths and weaknesses in comparison to an ideal system. The chapter concludes with a side-by-side analysis of all three systems according to six key characteristics.

DELTA SCAN

Delta Scan was developed as a tool for the Horizon Scanning Centre as part of the United Kingdom's national persistent forecasting effort. It is the sister system to Sigma Scan, which focuses on public policy and social issues. In contrast, Delta Scan focuses on technology. Initially guided by IFTF, the system first collected science and technology perspectives from over 250 experts in government, business, academia, and communications through workshops, interviews, and wikis. Then a team from the Horizon Scanning Centre reviewed projects and programs to determine strategic priorities, with the goal of augmenting overall technological capabilities. According to Horizon Scanning Center staff member Harry Woodroof, in his presentation to the committee on October 15, 2007, the goal of the Center was to perform

> the **systematic** examination of potential **threats, opportunities,** and likely developments, including but not restricted to those at the margins of current thinking and planning. Horizon scanning may explore novel and unexpected issues as well as persistent problems or trends (Woodroof, 2007).

Copyright National Academy of Sciences. All rights reserved.

The resulting technology perspectives were collected and synthesized into 100 papers by the Scanning Centre and the IFTF as they looked at potential developments in the field of science and technology over the next 50 years. The forecast comprised a short "outlook" and an Accompanying "snippet"; a set of overarching themes; and a map of the future. One example of a single-sentence outlook and its "snippet"—here, radio frequency identification—is as follows:

Tracking objects is made easy by RFID

> Radio Frequency Identification Devices (RFID) tagging systems will probably be widely used by government, industry, retailers and consumers to identify and track physical objects by 2015.
>
> This will vastly improve corporate inventory management, increase the efficiency of logistics, reduce loss (including through theft) at all stages between manufacturer and end-user, facilitate scientific research in hospitals by making it easier to track patients and lab samples, and make mislaid objects a thing of the past as individuals will be able to "google" and hence locate objects.

IFTF identified six science and technology (S&T) themes from the forecast:

- Small world,
- Intentional biology,
- Extended self,
- Mathematical world,
- Sensory transformation, and
- Lightweight infrastructure.

It also identified three meta themes: democratized innovation, transdisciplinarity, and emergence. The map of the future in Figure 6-1 was created by IFTF.

The results of the forecast were published both in a report and on the Horizon Scanning Centre's Web site. They were then were used to test strategic assumptions and to identify contingency trigger points to monitor. An impact audit was performed that weighed the identified risks against existing projects and priorities. The results were used to generate new questions and create fresh strategic priorities that could be fed back into the forecasting system. See Figure 6-2 for a diagram of the Delta Scan forecasting process.

Strengths and Weaknesses

A strength of this forecasting platform is that its goals, process, and approach were well defined from inception. It was designed to ensure that the architecture of the underlying data store could support and produce a forecast. The forecasting process was straightforward, practical, and used established forecasting methods such as interviews with experts and professionally led workshops. The system was developed with a modest level of resources and called on professional forecasters (IFTF staff) for help. Participants were drawn from areas of expertise that corresponded to stakeholders' priorities. The output of the forecast was clear and concise and helped to drive decision making, program direction, and resource allocation. In addition, the resulting time line and wiki are useful to future planners and forecasters. The system, though not persistent, was designed to be iterative.

The system's potential weaknesses include its lack of support for languages other than English, its emphasis on data of local rather than global origin, the exclusive use of expert views, and the single-dimensionality of the resulting forecast, which failed to offer alternatives to its vision of the future. The system was designed as an iterative platform for forecasting, but the time between forecasts is relatively long, and new signals do not immediately impact the forecast. The system requires the discrete linear processing of each step (goal setting, process design, interviews and scans, data normalization and preparation, workshops, synthesis, and audit of impact), and within each forecasting cycle all steps must be completed before a new forecast is produced. The system is therefore not designed to be persistent. While the resulting forecast was insightful, it was not particularly surprising. Topic areas

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

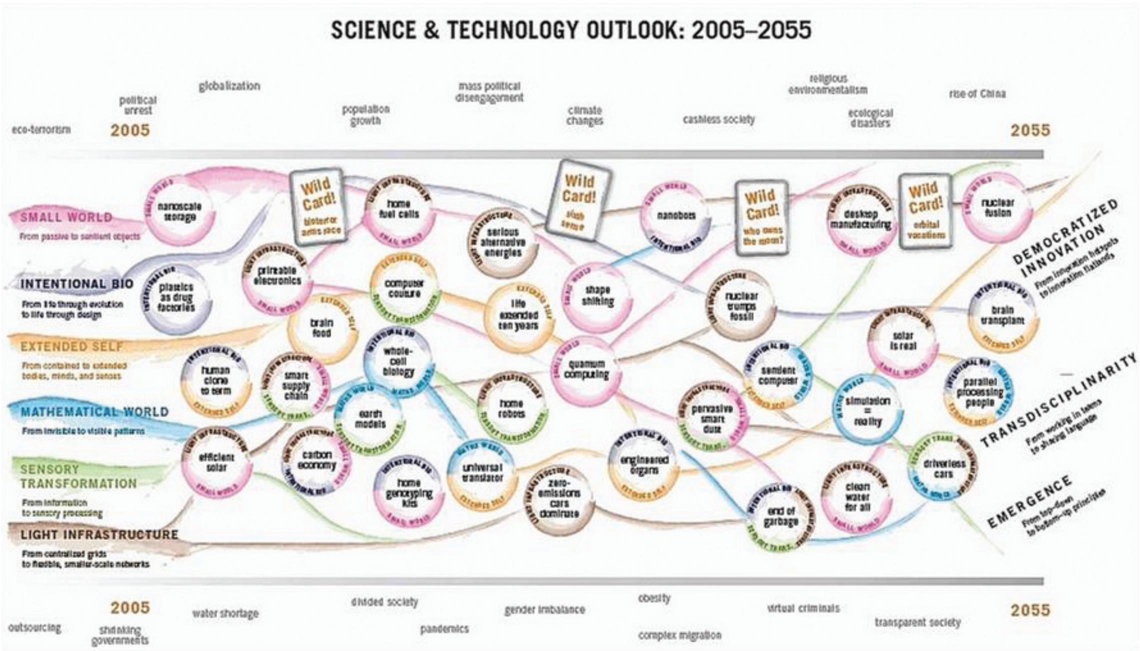


FIGURE 6-1 Science and technology outlook, 2005-2055. SOURCE: Woodroof, 2007. Crown Copyright, 2005. Produced for the U.K. Foresight Horizon Scanning Centre by the Institute for the Future. Used with permission from the U.K. Foresight Horizon Scanning Centre.

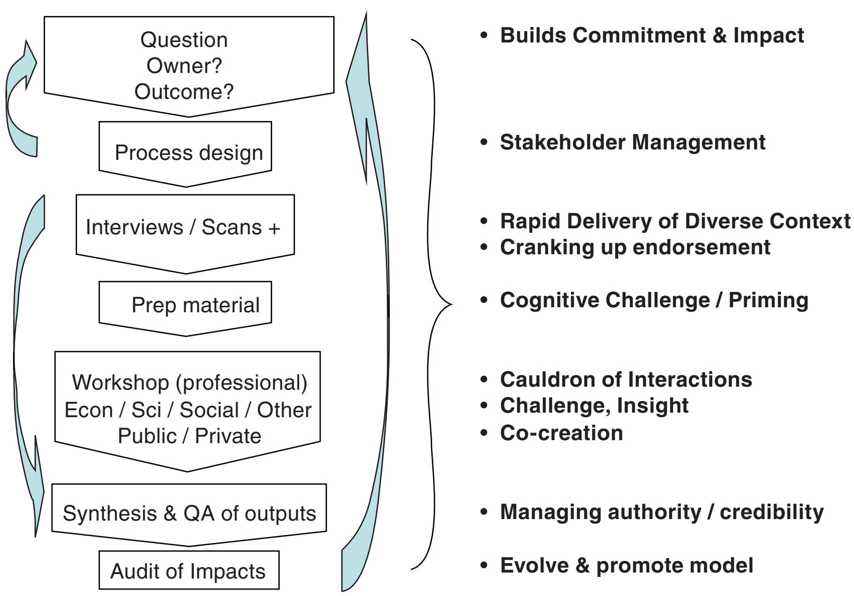


FIGURE 6-2 Process diagram from the Foresight Horizon Scanning Centre. SOURCE: Woodroof, 2007. Produced by the United Kingdom's Foresight Horizon Scanning Centre and used with the center's permission.

Copyright National Academy of Sciences. All rights reserved.

tended to be limited to well-understood technologies, and not enough attention was paid to possible wild cards or second-order effects. The committee would like to have seen more detailed regional analysis performed in the report and a greater emphasis on identification of possible signposts and tipping points.

TECHCAST

TechCast is an online research system which acts as a robust tool for pooling knowledge and forecasting technology. This system is designed to be highly flexible and can be used to gather expert data from an enterprise, a specific target group, a government, or the general public. TechCast relies on the observations of volunteer experts to forecast technological advances. The experts, who are either invited or self-nominated, are regularly surveyed on topics in their area of expertise. The resulting information is then used to create reports on an ad hoc basis.

TechCast was launched in 1998 by William E. Halal at George Washington University. The administrator of TechCast first scans a variety of sources to find technology that would be interesting to forecast. A wiki is produced that lists key events, data points, and trends. One hundred experts from around the world are then asked to make a prediction and comment on the predictions of other participants using a computational wiki system. Specifically, the experts are asked to predict when a new technology will be adopted, the scale of its market impact, and the expert's confidence in his or her own forecast. It also encourages experts to explain their prediction. Figure 6-3 is a diagram of the TechCast process (Halal, 2009).

This forecasting system is persistent: Each input into it automatically updates the forecast. TechCast.org has produced forecasts in 70 technology areas. Users can scan the prediction results using a wiki. Figure 6-4 summarizes the forecasts produced by the system. It describes when experts believe a new technology will reach adoption, the scale of the market, and experts' confidence in the prediction.

The computational wiki is automatically updated and its contents are added to a dashboard displaying the expert survey results, as seen in Figure 6-5.

Figure 6-6 summarizes a set of TechCast.org forecasts by time, market size, and average expert confidence, while Figure 6-7 summarizes the data by sector and the expected year of mainstream adoption.

Strengths and Weaknesses

TechCast is a very flexible platform and can support a wide range of prediction needs. Its strength lies in its simplicity. The system is entirely wiki based and does not require physical proximity of the forecasters. The four-step process is straightforward and simple to administer and can be maintained with few resources. It is easy to use and is persistent. Forecasters get instant results, and the site is as current as the last prediction. Output is clear and easy to understand. TechCast relies on a geographically diverse set of experts for its input; approximately half the contributors are foreign. Experts are prescreened and can comment and predict across disciplines, allowing the cross-fertilization of ideas and expertise. Participation from the expert pool is good and the administrator keeps experts engaged by frequently asking for new input to new questions generated within the system.

The TechCast.org Web site has some drawbacks. First of all, it is dependent on the administrators to select topics for expert commentary. The first two steps in TechCast's process are performed by administrator, and the methodologies employed to screen and to analyze topics are not disclosed. The system's output is also highly influenced by the composition of the expert pool, and it is unclear what the criteria are for inclusion. The TechCast.org Web site is currently English-only and does not support regional analysis. The system of communication is relatively basic, depending solely on wikis for interactions between experts. Finally, while the system analyzes background data, it does not publish the specific signals, signposts, or tipping points necessary for continued tracking of forecasts.

Copyright National Academy of Sciences. All rights reserved.

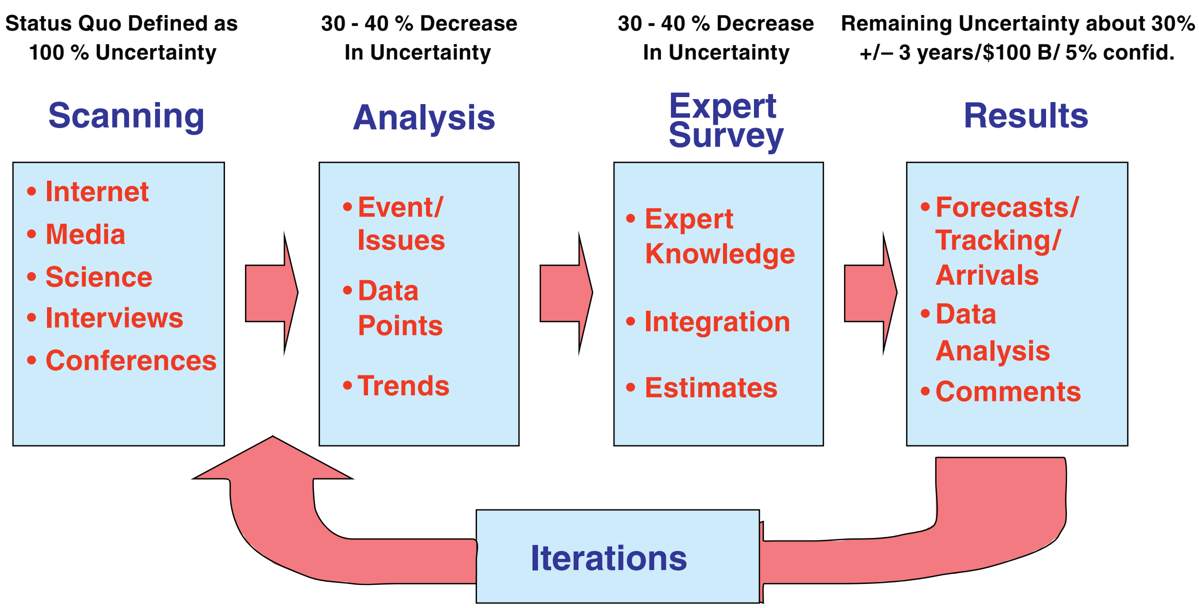


FIGURE 6-3 TechCast online research system. SOURCE: Halal, 2009.

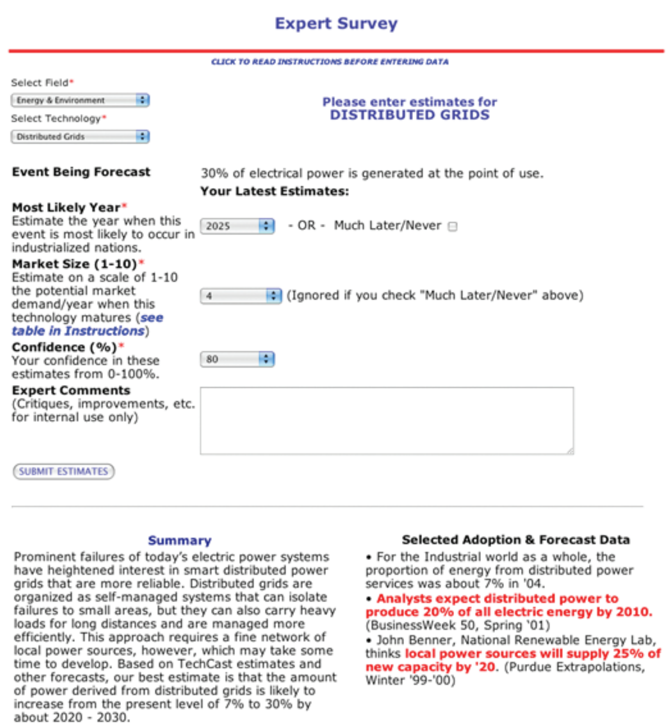


FIGURE 6-4 Expert survey. SOURCE: Halal, 2009.

Copyright National Academy of Sciences. All rights reserved.

Persistent Forecasting of Disruptive Technologies

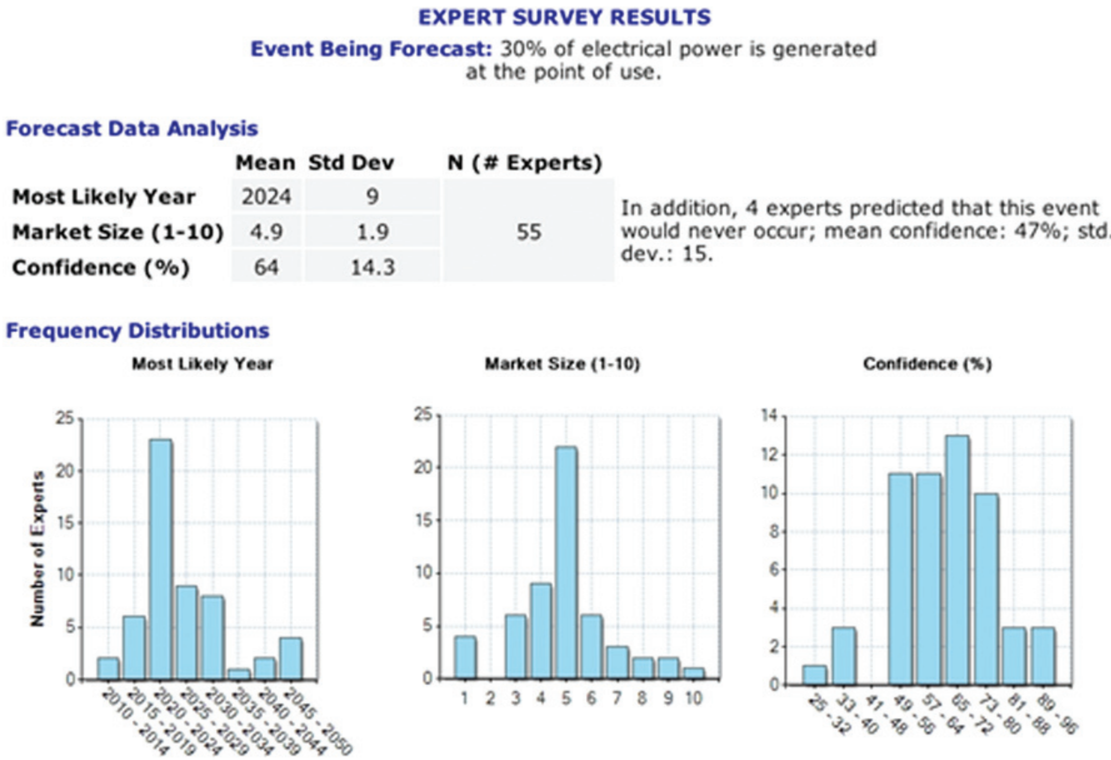


FIGURE 6-5 Result of expert survey results. SOURCE: Halal, 2009.

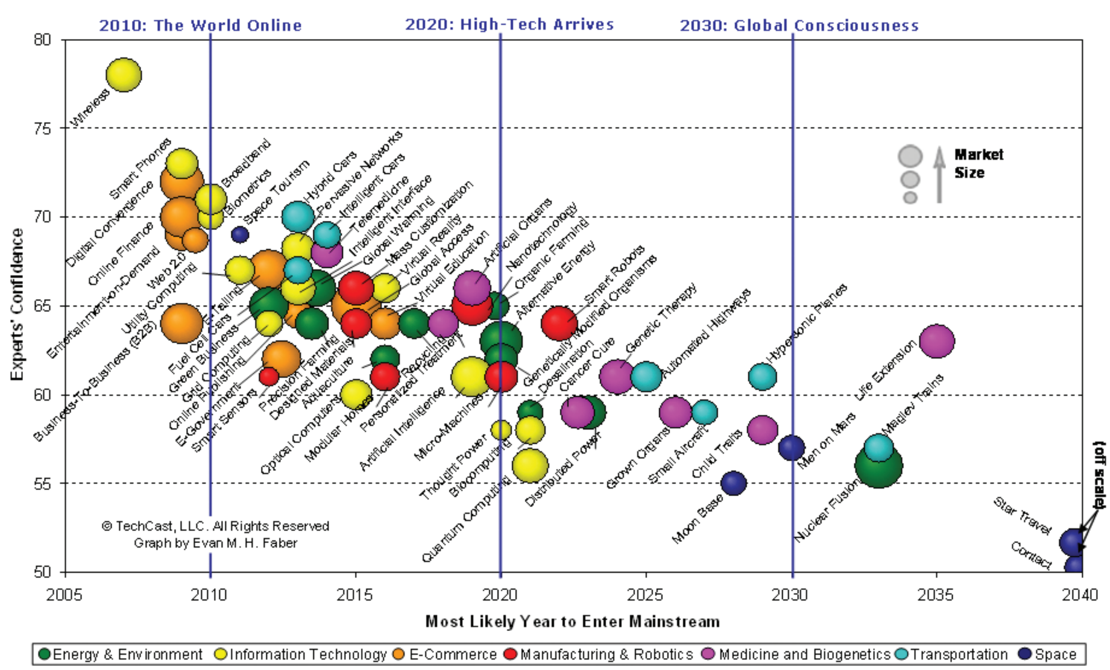


FIGURE 6-6 Longitudinal summary of forecasts. SOURCE: Halal, 2009.

Copyright National Academy of Sciences. All rights reserved.

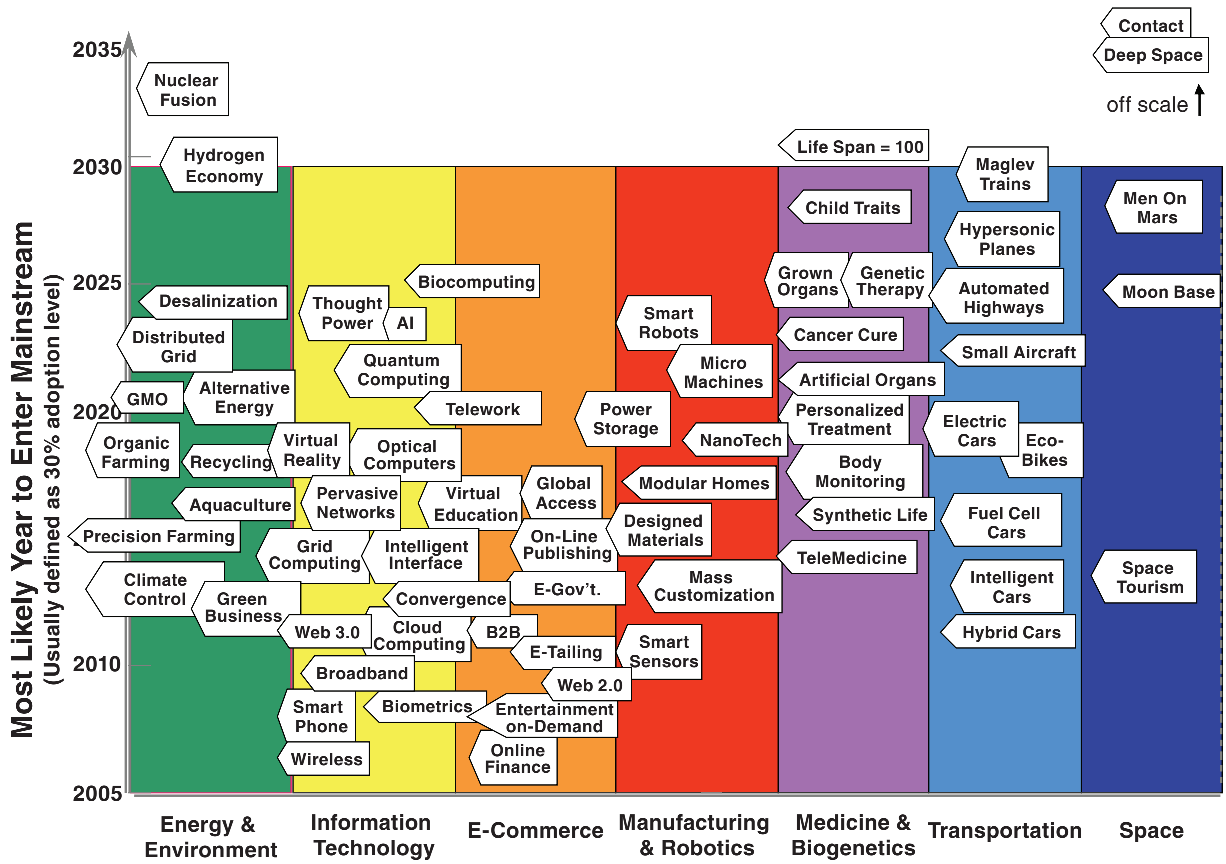


FIGURE 6-7 Summary of forecast results. SOURCE: Halal, 2009.

X2 (SIGNTIFIC)

The X2 project, under development by IFTF, is a re-envisioning of the Victorian era X-Club, designed to foster collaboration among diverse groups by a combination of social networking (including Facebook and Digg), futurism, and forecasting. It is a novel system with a greater degree of software sophistication than the other systems described. IFTF recently gave X2 a new name—Signtific—to serve as a global collaborative research platform created to identify and facilitate discussions around future disruptions, opportunities, and trends in science and technology.[1]

The X2 system combines workshops, an online, wiki-based platform, and ARGs to produce a forecast. It has three main activities: signal development, forecast generation, and “big story” creation. Big story creation is the X2 creators’ version of alternative future generation. Figure 6-8 shows their methodology.

The first component of X2 is expert workshops. IFTF held seven workshops around the world, with each workshop having at least 15 and sometimes more than 30 expert participants. All workshops were conducted in English. Workshops were cohosted by other organizations and employed new visualization technologies such as ZuiPrezi. A typical workshop agenda included the following: headline (theme), futures of science, geographies of science, signal entry, and breakout.

Figure 6-9 is the output of an X2 workshop.

[1]Available at http://www.iftf.org/node/939. Last accessed May 6, 2009.

Copyright National Academy of Sciences. All rights reserved.

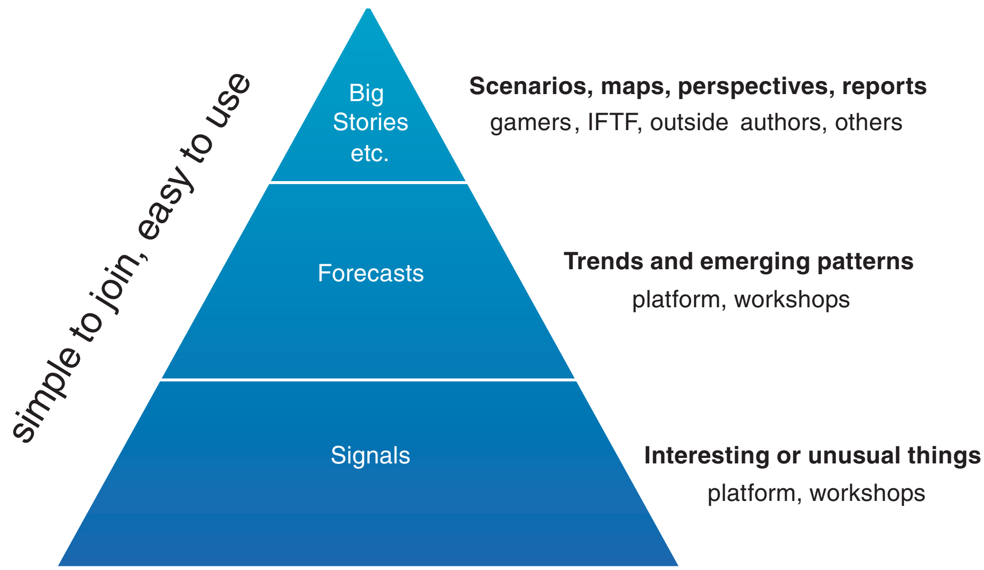


FIGURE 6-8 X2 content and methodology. SOURCE: Castro and Crawford, 2008. Courtesy of the Institute for the Future.

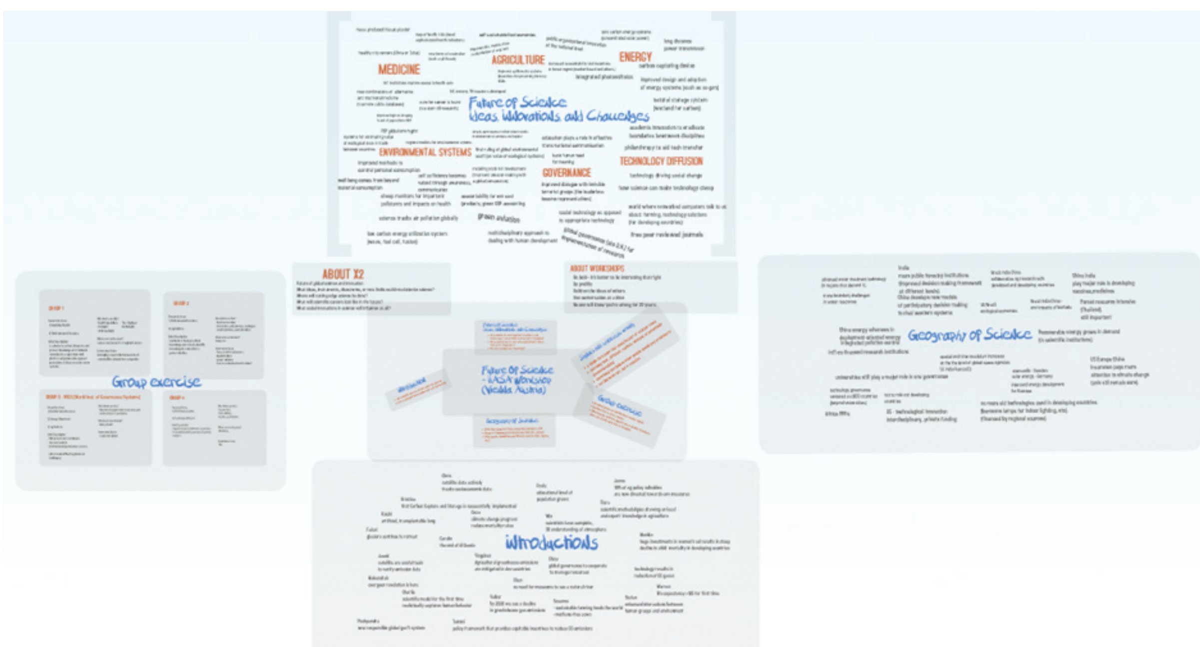


FIGURE 6-9 X2 Workshop output. SOURCE: Castro and Crawford, 2008. Courtesy of the Institute for the Future.

Copyright National Academy of Sciences. All rights reserved.

The second component of X2 was an interactive online platform. The platform allowed experts to post signals of interest to specific subject groups. As of November 2008, 235 experts had been invited by IFTF to participate in the platform. The 28 subject groups collectively produced 697 signals, 262 forecasts, and 11 perspectives. Signals were inputted by experts (Figure 6-10), who suggested questions to be answered. Topics were tagged, and abstracts could be added by experts.

Experts could comment and rate the likelihood and potential impact of any signal created. They would then use these signals to generate sample forecasts such as the following:

> "Growing infrastructures for 'citizen science' will help shape twenty-first century science."
> —Hyungsub Choi, Pennsylvania
>
> "Soft technology will be a protagonist for innovations in the twenty-first century."
> —Zhouying Jin, China
>
> "Bayesian networks utilized in creating more mobile social networks."
> —Emma Terama, Austria

From predictions captured by the X2 platform, IFTF then proceeded to generate "perspectives." Sample perspectives included these:

- The Indian Ocean as a new nexus for science,
- Islam's coming scientific revolution,
- Designing the next revolution in science,
- Will green chemistry be the central science of the twenty-first century?
- The interdisciplinary future of energy research,
- The transformation of science parks, and
- Linking innovation to manufacturing.

The third component of the X2 system is the use of "thought experiments" conducted in the form of games. IFTF employed ARGs to flush out an alternative future using crowd sourcing. Players accept the premise of the alternative future and then role-play. The game is guided by "game masters" who monitor the progress of the game and generate events within the scenario. The philosophy behind the creation of the ARG is to develop engaging scenarios that reflect perspectives generated by game players and that could serve as a foundation for discussion using Web-based social media tools. IFTF felt it was equally important to develop an appropriate community architecture focused on attracting participants and game masters and to clearly communicate the promise of the game to the players.

Box 6-1 shows a sample scenario, and Figure 6-11 shows a sample game screen.

As mentioned previously, the games are crowd sourced. The ARG is promoted on the Internet and is open for players from around the world to play. The games are used to gain a better understanding of the impact of various perspectives and future scenarios.

Strengths and Weaknesses

X2 is an interesting mix of forecasting methodologies. It combines traditional Delphi approaches with innovative methods such as ARGs and expert wikis. The system is managed by experienced professional forecasters, draws on experts to flush out signals and to forecast, and then calls on the crowd (through the use of gaming) to understand impact. The workshops, which are held around the world, are attended by a diverse set of experts. The X2 platform is a persistent system that allows experts to participate at their convenience; the workshops and games are organized events. It does an excellent job of allowing experts to create categories, input signals, and discuss potentially disruptive technologies. Finally, ARG is an innovative and effective way to flush out the potential impact of an alternative future. It does a good job of attracting players from around the world to participate in an engaging role-playing exercise.

Copyright National Academy of Sciences. All rights reserved.

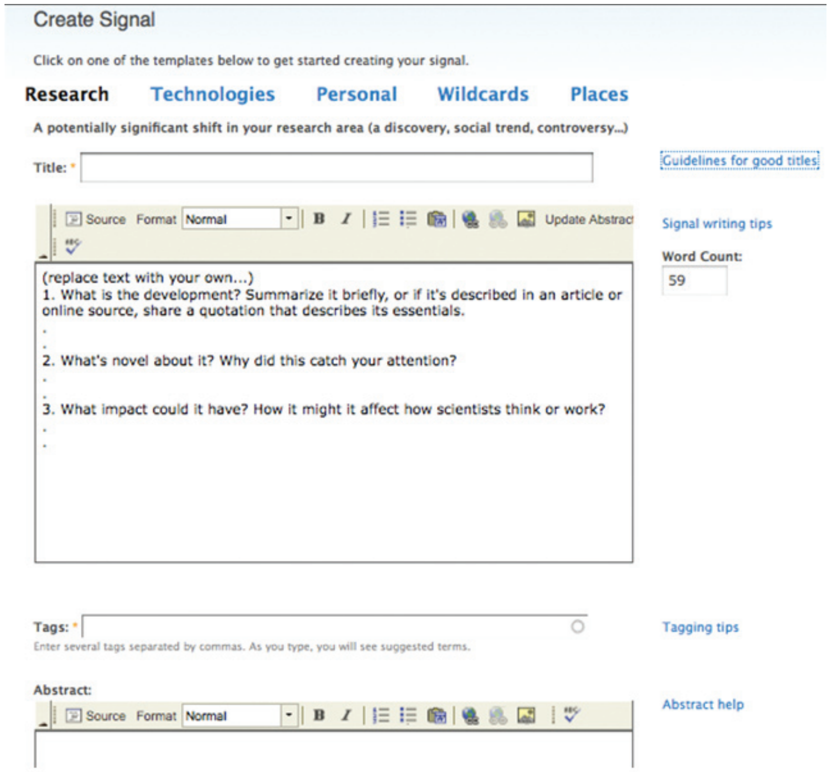


FIGURE 6-10 Expert signal framework of X2. SOURCE: Castro and Crawford, 2008. Courtesy of the Institute for the Future.

BOX 6-1
Sample X2 Game Scenario: Wall Street Becomes the Mechanism for Setting the Scientific Agenda and Provides the Financing

It's the year 2020, and wealthy individual entrepreneurs are at the forefront of scientific and technological innovation. . . . Innovation moves from institutional to individual.

- Who are you in 2020? How does this new model of innovation affect you?
- If you are a future Xoogler, what research would you fund?
- If you are not wealthy, does the growing influence of individuals and less government oversight concern you? What would you do?
- How might this change the relationship between amateur and professional scientists?

SOURCE: Castro and Crawford, 2008. Courtesy of the Institute for the Future.

Copyright National Academy of Sciences. All rights reserved.

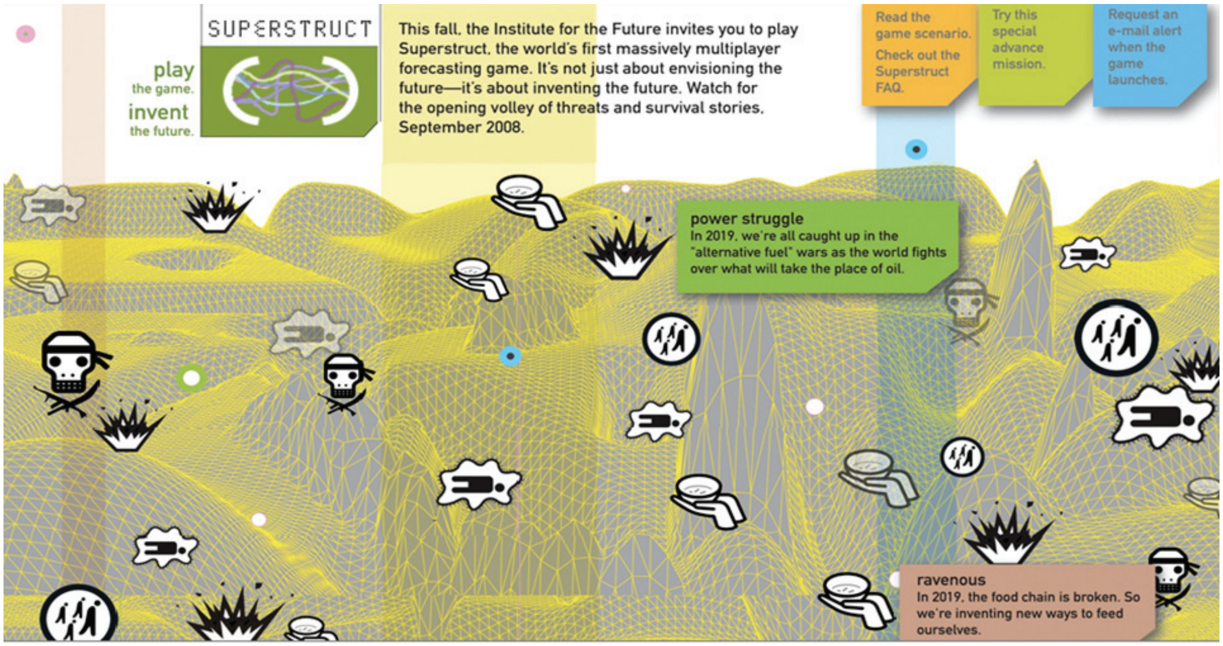


FIGURE 6-11 Sample game screen of an ARG game used by IFTF. SOURCE: Castro and Crawford, 2008. Courtesy of the Institute for the Future.

In spite of X2's many innovations, the system had some shortcomings. Each component of the X2 process required participants to speak English, and none of the workshops were held in a language other than English. The committee was also concerned that not enough attention was paid to making sure that the participants in the workshops were diverse enough to represent the science and technology community of the region and that there was only limited participation from young scientists, researchers, technologists, and entrepreneurs. More thought could have also been given to the selection of locations for the workshops. The committee felt strongly that X2 workshops should seek out places with developing knowledge and techno clusters that had not already been surveyed to gain technology forecasts.

There were also concerns that the X2 platform was not engaging enough to encourage continuous participation by the experts and that over 50 percent of the signals were generated from U.S. experts. The participation in each forecast is too sparse to allow the wiki to collect and compute statistically meaningful likelihood and impact projections. It would also be useful to specifically ask the experts to predict a realization date for each forecast as a part of gathering data for the computational wiki.

EVALUATION OF FORECASTING PLATFORMS

The committee's evaluations of the three forecasting systems, summarized in Table 6-1, are seen as preliminary and subject to additional discussion in later reports. While none of the systems met all the requirements of an ideal persistent forecasting system laid out by the committee, all had elements that were valuable.

The committee has already seen great potential in existing forecasting systems such as Delta Scan, TechCast, and X2 (Signtific). These projects demonstrate many of the concepts presented in this report and give the committee confidence that an open, persistent forecasting platform for disruptive technologies can be created. Any of these existing forecasting systems could serve as the foundation for a more robust system. Significant insight can be gained even with limited or partial implementation.

Copyright National Academy of Sciences. All rights reserved.

TABLE 6-1 Initial Evaluation of Existing Forecasting Systems

	Tech Cast	Signtific (X2)	Delta Scan
Data sources	*Partially meets*. Largely from selected panel experts. Other sourcing methods and geographic sourcing not apparent. Open to invited members only. Novel data sources, collection techniques, and data audit methods not apparent. English only.	*Partially meets*. Open system. Multiple data sources (stewards, workshops, games) and baseline data. Geographical diversity improving (workshops, Web site) but still is English only. Participant's profiles captured. Some applications of novel data sourcing and collection techniques. Data audit methods not apparent.	*Partially meets*. Open to access but not to contribute. Data gathered from more than 250 experts with a wide array of backgrounds through workshops and interviews. English only. Novel data sources, collection techniques, and data audit methods not apparent.
Forecast methods	*Partially meets*. Self-selected expert opinion with some predictive elements. Part qualitative and quantitative. No apparent barriers to recruiting experts.	*Partially meets*. Forecasts and signals derived from stewards, experts, and public via workshops and games. Signals and forecasts largely qualitative. Quantitative methods not apparent.	*Partially meets*. Principally expert opinion. Forecast supplied by the Institute for the Future. No apparent way for the public to contribute or collaborate.
Forecast team	*Partially meets*. Self-selected experts and small team. English only. No apparent barriers to recruiting experts. Methods to assess expert diversity, country or quals not published. No public participation.	*Partially meets*. Team consists of employees, experts, and public. Public participation strong and growing in some areas—7,000 participants in the last AGR. More limited public participation in signal generation and forecasting. Evidence of third-party community development, collaboration, and initiative becoming apparent. English only.	*Partially meets*. Forecasts supplied by the Institute for the Future. Appears to be English only. No apparent public participation. Methods to assess diversity of experts by country, culture, discipline, etc. not apparent.
Data output	*Partially meets.* Quantitative and qualitative. Each forecast quantifies estimated time of realization, confidence levels, market size, and range of dispersion. Qualitative assessments of forecast strengths and weaknesses. Visualization limited to static graphs. Unclear if data are exportable.	*Partially meets.* Principally qualitative. Quantitative representation is limited or not apparent. Third-party access (and export capabilities) to the data on player behavior is not apparent.	*Largely meets.* Qualitative with some quantitative. 1-5 scale assessment of impact, likelihood, and controversy. Qualitative assessment of geographical impact. Signals, enablers, inhibitors, Centers of excellence, data sources, analogies, word tags and links identified. Visualization and navigation could be strengthened.
Processing tools	*Limited.* Some enablers and inhibitors identified in forecast narrative. Processing done by the expert community. Diversity of experts unclear. Other processing tools (dashboards, data visualization, signal and link processing) are not apparent.	*Limited.* Some enablers and inhibitors identified by the community. Diversity of the community processing the data appears to be improving. Other processing tools (dashboards, data visualization, signal and link processing) are not apparent.	*Limited.* Signals, enablers, inhibitors identified but no apparent way to automatically measure progress toward thresholds. Diversity of community processing data unclear. Other processing tools (dashboards, data visualization, signal and link processing) are not apparent.

continues

Copyright National Academy of Sciences. All rights reserved.

TABLE 6-1 Continued

	Tech Cast	Signtific (X2)	Delta Scan
System attributes	*Partially meets.* System is persistent but not open. Bias mitigation processes not apparent. Degree of scalability unclear. English only. Intuitive system with limited communication tools.	*Partially meets.* System is persistent and open. Bias mitigation processes not apparent. Degree of scalability unclear. English only. Additional communication tools could improve usability.	*Limited.* Open to access but not to participate. System not persistent (last updated in 2006). Bias mitigation processes not apparent. Degree of scalability unclear. English only. Additional communication tools could improve usability.
Summary	*Partially meets.* TechCast partially meets the attributes of the persistent forecasting system with strengths in ease of use and in quantifying the probability of occurrence, impact, and forecast timing. Could improve by broadening methods of data sourcing, utilizing more forecasting techniques, incorporating multiple languages, diversifying the forecast team (including the public), and strengthening data output and processing tools. The forecast produced is a single view of the future synthesized by the system operator.	*Partially meets.* X2 partially meets the attributes of the persistent forecasting system, with strength in openness, qualitative data capture, multiple data sources, and multiple forecasting methods. Could improve by adding multiple language support, strengthening quantitative forecasting methods, processing tools, and visualization techniques. The system lacks consistent participation from users and forecasters. Forecast suffers from inadequate preparation of the initial problem set and definition of the scope of the forecasting mission.	*Partially meets.* Delta Scan partially meets the attributes of the ideal forecasting system with particular strength in the robustness of the data forecast output. The system could be strengthened by being persistent and including additional data sources, forecast methods, public participation, native language support, and better processing tools.

REFERENCES

Castro, Cesar, and Mathias Crawford. 2008. X2: Threats, opportunities, and advances in science & technology, Presentation to the committee on November 6 by the Research Director for the Institute for the Future.

Halal, William E. 2009. Forecasting the technology revolution, Presentation to the committee on August 3 by the President of TechCast, LLC.

Woodroof, Harry. 2007. Delta Scan, Uses in U.K. government, Presentation to the committee on October 15 by the Leader, Delta (S&T) Scan, Horizon Scanning Centre, Government Office for Science, United Kingdom.

Copyright National Academy of Sciences. All rights reserved.

7

Conclusion

Technology forecasting is strategically both a defensive and offensive activity. It can assist in resource allocation and minimize the adverse impacts or maximize the favorable impacts of game-changing technology trends. In a general sense, it is wise to be circumspect by analyzing the state of trend-setting technologies, their future outlook, and their potential disruptive impact on industries, society, security, and the economy. To paraphrase Winston Churchill, the goal of forecasting is not to predict the future but to tell you what you need to know to take meaningful action in the present.

This final chapter summarizes and condenses key points from throughout the report, presented in the form, first, of a checklist of important system attributes and, second, steps to build a persistent forecasting system for disruptive technologies.

BENCHMARKING A PERSISTENT FORECASTING SYSTEM

Table 7-1 describes the attributes of a well-designed, persistent forecasting system by component of the system.

STEPS TO BUILD A PERSISTENT FORECASTING SYSTEM FOR DISRUPTIVE TECHNOLOGIES

An open and persistent system offers the opportunity to use a richer set of data inputs, forecasting methods, assessments, and analytical capabilities to produce more useful forecasts. A poorly designed system could be overwhelmed by information overload or missed correlations due to poor data organization techniques, or it might never achieve a critical mass of expert or public participation. The committee believes that an open and persistent forecasting system requires substantially greater investment in both planning and implementation than traditional forecasting approaches. Eight steps to building a persistent forecasting system are outlined next:

1. *Define the mission.* The designers of the system should conduct in-depth interviews with key system stakeholders to understand their objectives. The mission or goals of the stakeholders are likely to change and expand over time. Therefore, regular meetings should be held to identify new priorities and methods to improve the existing system (feedback loop).

Copyright National Academy of Sciences. All rights reserved.

TABLE 7-1 Attributes of an Ideal Forecasting System

Category	Attributes	Description
Data sources	Diversity of people and methods	Data should come from broad range of experts and participants from diverse countries, cultures, ages, levels of wealth, education, expertise, etc.
	Diversity of sources	Data should be from a broad range of sources and formats, with particular attention to non-U.S. and non-English-speaking areas.
	Metadata	Key metadata should be captured, such as where, when, and how they were sourced as well as quality, measurements of interest, and resolution of data. Patterns can be distinguished by region, age of contributor, quality, etc.
	Data liquidity, credibility, accuracy, frequency, source reliability	Should use multiple methods to ensure data accuracy, reliability, relevancy, timeliness, and frequency. Data should be characterized and stored in a way that makes them interchangeable/interoperable regardless of format or source from which they were gathered.
	Baseline data	Collect historical, trend, and key reference data that can be used for comparison and analysis of new collections.
	Diversity of qualitative data sources	Gather data using a variety of qualitative methods such as workshops, games, simulations, opinions, text mining, or results from other technology forecasts.
	Diversity of quantitative data sources	Data should be sourced from a variety of data sets and types, including commercial and proprietary sources.
Forecasting methods	Multiple forecasting methodologies	System should utilize multiple forecasting methodologies as inputs to the system to reduce bias and to capture the widest range of possible forecast futures. Backcasting should be one of the processes used with a handful of initial future scenarios to begin the process of identifying key enablers, inhibitors, and drivers of potential disruptions, with particular attention to identifying measurements of interest, signposts, and tipping points. Vision-widening techniques (brainstorming, interviews, workshops, and open-source contributions) should be key components of the forecasting process.
	Novel methods	System should consider incorporating novel methods such as ARG, virtual worlds, social networks, prediction markets, and simulations.
	Qualitative	System utilizes qualitative forecasting methodologies.
	Quantitative	System utilizes quantitative forecasting methodologies.
Forecasting team	Expert diversity and ongoing recruitment	Team should be diversified by country, culture, age, and technology disciplines, etc. Use culturally appropriate incentives to maintain required levels of participation.
	Ongoing recruitment	Renew personnel and continually recruit new team members to ensure freshness and diversity of perspectives.
	Public participation	Broad and diverse public participation is critical for capturing a broad range of views, signals, and forecasts. Application of culturally appropriate incentives and viral techniques to reach and maintain a critical mass of public participation.
Data output	Readily available	Data should be readily available, exportable, and easily disseminated beyond the system in commonly used formats.
	Intuitive presentation	Output should be presented in a way that is informative and intuitive. Utilization of dashboards and advanced visualization tools.
	Quantitative and qualitative	Raw quantitative and qualitative data and interpretive elements are readily available for further analysis.

continues

Copyright National Academy of Sciences. All rights reserved.

TABLE 7-1 Continued

Category	Attributes	Description
Processing tools and methods	Enablers/inhibitors	Facilitate methods to identify and monitor key enablers, inhibitors, measurements of interest, signals, signposts, and tipping points that contribute to or serve as a warning of a pending disruption.
	Multiple perspectives—qualitative/human	Humans with varying backgrounds, of diverse cultures, ages, and expertise analyze data employing multiple tools and methods.
	Outlier events/weak signal detection	Tools and methods for finding weak signals or extreme outliers in large data sets. Tools and processes to track and monitor changes and rates of change in linkages between data are essential.
	Impact assessment processes	Employ methods to assess impact of potential disruptive technology and recommend potential methods to mitigate or capitalize on the disruption.
	Threshold levels and escalation processes	Employ methods to set and modify warning signal threshold levels and escalate potentially high-impact signals or developments to other analytical perspectives or decision makers.
	Forecast data object flexibility	Store data using object-oriented structures. The data objects being used to forecast can show flexibility in how they are stored. Data objects can be categorized in several ways, including but not limited to disruptive research, disruptive technologies, and disruptive events. Relationships and structures between these objects can be restructured and analyzed.
	Visualization	Data should be visually represented intuitively and with interactive controls. System should support geospatial and temporal visualizations.
System attributes	Bias mitigation processes	Robust ongoing internal and external bias mitigation processes are in place.
	Review and self-improvement	Processes in place to review and assess why prior disruptions were either accurately predicted or missed by the platform.
	Persistence	Forecasts are ongoing and in real time.
	Availability	System should be continuously accessible and globally available.
	Openness	System should be open and accessible to all to contribute data, provide forecasts, analyze data, and foster community participation. The data, forecast, and signals generated from the system are publically available.
	Scalability/flexibility (hardware and software)	System should scale to accommodate large numbers of users and large datasets utilizing standardized data and interchange formats.
	Controlled vocabulary	Use standard vernacular for system benchmarks (watch, warning, signal, etc.), language and tagging.
	Multiple native language support	Data should be gathered, processed, exchanged, translated, and disseminated in a broad range of languages.
	Incentives	Reputation, knowledge, recognition, and other methods for incentivizing participation. Monetary incentives could be considered to get certain expert sources and research initiatives to contribute.
	Ease of use (accessibility, communication tools, intuitive)	Make the site easily accessible. Navigation around the site should be intuitive and have communication tools to facilitate usability and community development.
Environmental considerations	Financial support	The system must be underpinned by long-term and substantial financial support to ensure that the platform can achieve its mission.
	Data protection	Data must be protected from outages, malicious attack, or intentional manipulation. Robust back-up and recovery processes are essential.
	Auditing and review processes	Put processes in place to regularly review platform strengths and weaknesses, biases, why disruptions were missed, and to audit changes to data, system, architecture, hardware, or software components.

Copyright National Academy of Sciences. All rights reserved.

2. *Scope the mission.* Define which people and resources are required to successfully build the system and meet mission objectives:
   —Secure substantial and sufficient long-term financial support.
   —Establish a small team with strong leadership for initial analysis and synthesis. This team will target methods and sources for the forecast, as well as synthesize results. To provide continuity, this team should produce regular updates along with the overall forecast. It should also learn over time from its successes and failures and adjust accordingly. Experience suggests that such teams can improve over time. A key success factor for this group is diversity of skills, expertise, culture, and demographics.
   —Identify, design, and build the necessary systems and processes required to support a highly scalable, persistent forecasting system.
   —Identify the best way to organize disparate sets of structured and unstructured data.
3. *Select forecasting methodologies.* The requirements of the mission and the availability of data and resources will determine the appropriate methodologies for recognizing key precursors to disruptions, identifying as many potential disruptive events as possible.
   —*Backcasting*. Identify potential future disruptions and work backwards to reveal key enablers, inhibitors, risks, uncertainties, and force drivers necessary for that disruption to occur. Distinguish key measurements of interest that can be tracked and used for signaling. Particular attention should be focused on identifying potentially important signals, signposts, and tipping points for that disruption. The backcasting process should help to crystallize the minimum data feeds and experts needed to warn of potential disruptions.
   —*Vision-widening techniques.* Utilize traditional means (brainstorming, workshops, trend analysis, the Delphi method) as well as novel vision-widening techniques (open source, ARG, predictive markets, social networks) to identify other potentially disruptive outcomes. The vision-widening process should reveal additional information sources and expertise required by system operators.
4. *Gather information from key experts and information sources.* The process of gathering information from people and other sources will need to be ongoing.
   —*Assign metadata.* As data are gathered, they should be tagged. Key tags include the source, when and where the data were gathered, and appropriate quality ratings (reliability, completeness, consistency, and trust).
   —*Assess data sources.* Select data sources that are relevant to the forecasting exercise. Do not "boil the ocean" and attempt to process all available data but instead process the data that are relevant or potentially relevant to achieve the goals of the forecast. State if the data are readily available, semiavailable (proprietary data or periodically available data), or unavailable. Relevant data feeds should be integrated into the system to support automated processing, and proxies should be developed where data are critical but unavailable. Where proprietary data sets are important, negotiating access should be explored. Information-gathering from human sources should be continuous, utilizing both traditional means (workshops, the Delphi method, interviews) and novel (gaming, predictive markets, ARG) methods.
   —*Normalize data.* Reduce semantic inconsistency by developing domain-specific anthologies and by employing unstructured data-processing methods such as data mining, text analytics, and link analysis for creating structured data from unstructured data; using semantic web technologies; and utilizing modern extract, transform, and load (ETL) tools to normalize dissimilar datasets.
   —*Where possible, gather historical reference data.* Breaks in long-running trends are often signals of major disruptions and can be observed in the historical data. Historical reference data are useful for pattern recognition and trend analysis.
   —*Assess and mitigate biases in data gathering.* Ensure that the data being gathered are from multiple regions and cultures and that the human sources are diversified by age, language, region, culture, education, religion, and so on. Are the incentives attracting diverse, highly qualified participants? Determine which tools and incentives would attract and quality of experts to participate. If not, determine which tools and incentives would attract and retain such participants.

Copyright National Academy of Sciences. All rights reserved.

5. *Prioritize forecasted technologies.* System operators must assess the potential impact of the forecast on society, resources, etc., and the lead time, from warning to event, to determine appropriate signals to track, threshold levels, and optimal resource allocation methods.
6. *Optimize process, monitor, and report tools.* Processing and monitoring tools should be optimized to look for outliers and to find weak signals and signposts in noisy information environments. System users (decision makers, experts, and the public) should be able to access and analyze the real-time status of critical potential disruptions and the progress of a critical disruption relative to historical trends and breakthrough points as well as to develop an overall picture of the range of possible disruptions. In addition, the following tools should be included at a minimum:
   —*Search/query/standing query.* On ideas, text, images and other media, linkages, signals, and the like.
   —*Interactive interface.* User ability to control and manipulate time, scope, scale, and other variables.
   —*Signal threshold control.* Signals and/or alerts should be generated when certain thresholds are met or events occur. In general, low thresholds should be used for high-impact signals, and high thresholds for low-impact signals.
   —*Analytical tools.* The system should incorporate a rich set of tools, including link analytics, pattern recognition, extrapolation, S-curves, and diffusion rates.
   —*User-controlled visualization, presentation, and dashboard tools.* Data should be presented using multiple visualization methods and formats. Dashboards should be designed to engage with decision makers.
   —*Standard and special reports.* The system should generate standardized as well as user-defined reports. Templates should be developed to enhance ease of use and to support comparison and analysis across reporting periods.
7. *Develop resource allocation and decision support tools.* Decision makers will need tools to constantly track and optimize their resource portfolios and decisions in response to changes in the probabilities of potential disruptions.
8. *Assess, audit, provide feedback, and improve forecasts and forecasting methodologies.* Process and system improvement should be ongoing. Operators should consider reviewing why previous disruptions were missed (bias, lack of information, lack of vision, poor processes, or lack of resources and the like) and what could be done to overcome these biases. Operators of the system should seek feedback from users and decision makers about the usefulness of the forecasts derived from the site and the impact the forecast had on decision making. An understanding of how users apply the forecasts in day-to-day decision making would help operators to refine the system. Finally, audit tracking and system protection processes must be put in place to ensure that system results are not purposefully hidden, manipulated, or lost.

CONCLUSION

Postmortem analysis of disruptive events often reveals that all the information necessary to forecast a disruptive event was available but missed for a variety of reasons, including the following:

- Not knowing enough to ask a question,
- Asking the right question at the wrong time,
- Assuming that future developments will resemble past developments,
- Assuming one's beliefs are held by everyone,
- Fragmentation of the information,
- Information overload,
- Bias (institutional, communal, personal), and
- Lack of vision.

The committee believes a well-designed persistent forecasting system focused on continual self-improvement and bias mitigation can address many of these issues by reducing the scope for uncertainty and likelihood of surprise and leading to improved decision making and resource allocation.

Copyright National Academy of Sciences. All rights reserved.

The construction and operation of a persistent forecasting system is a large and complex task. It is important to note that the creation of an ideal system is iterative and may take several years to perfect. System operators and sponsors must improve the system by installing processes to continually assess, audit, and evaluate its strengths and weaknesses. These assessments should be performed by both internal stakeholders and unaffiliated outsiders.

Persistent systems require continuing sponsorship and organizational support. Building and maintaining an ideal, open, and persistent forecasting platform will not be inexpensive. A professional staff is needed to build and operate it, and it requires a robust infrastructure, access to quality data, enabling technologies, and marketing to attract a broad range of participants. Consistent and reliable funding is critical to the successful development, implementation, and operation of the system.

Copyright National Academy of Sciences. All rights reserved.

Appendixes

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.

Appendix A

Biographical Sketches of Committee Members

Gilman Louie, *Chair*, is a partner of Alsop Louie Partners, a venture capital company. Mr. Louie is a former president and CEO of In-Q-Tel, the venture capital group helping to deliver new technologies to the Central Intelligence Agency (CIA) and the intelligence community. Before helping found In-Q-Tel, Mr. Louie served as Hasbro Interactive's chief creative officer and as general manager of the Games.com group, where he was responsible for creating and implementing the business plan for Hasbro's Internet games site. Before joining Hasbro, he served as chief executive of the Nexa Corporation; Sphere, Inc.; and Spectrum HoloByte, Inc. As a pioneer in the interactive entertainment industry, Mr. Louie's successes include the Falcon, F-16 flight simulator, and Tetris, which he brought over from the Soviet Union. He has served on the boards of directors of Wizards of the Coast; the Total Entertainment Network; Direct Language; Ribbit; and FASA Interactive. He currently serves as a member of the technical advisory group of the Senate Select Committee for Intelligence and was an active member of the Markle Foundation Task Force on National Security and the Information Age.

Prithwish Basu is a senior scientist in the Network Research Group at BBN Technologies in Cambridge, Massachusetts. He is the principal investigator at BBN on multiple networking programs funded by U.S. Army Research Laboratory, namely, Collaborative Technology Alliance and the U.S./U.K. International Technology Alliance. He is also the chief architect at BBN on DARPA's Disruption-Tolerant Networking program. In 2006 he was named to MIT *Technology Review*'s list of Top Innovators Under 35 (TR35). His current research interests include theoretical as well as practical aspects of disruption-tolerant networking; energy-efficient medium access control, routing, and synchronization in wireless ad hoc and sensor networks; and robot networking. Recently he has also been interested in network science and is also exploring the use of biological metaphors for developing new networking algorithms. He received a B.Tech. in computer science and engineering from the Indian Institute of Technology in Delhi and M.S. (1999) and Ph.D. (2003) degrees in computer engineering from Boston University. Dr. Basu has co-authored over 30 conference and journal articles and two invited book chapters and has two patents pending. He is a senior member of the Institute of Electrical and Electronics Engineers, the Association for Computing Machinery, and Sigma Xi and has served on the technical program committees and organizing committees of several leading networking conferences such as IEEE INFOCOM.

Harry Blount is currently founder and CEO of Gold Vision Ventures. Mr. Blount is chairman of the Futures Committee for the Tech Museum of Innovation and is chairman of the Advisory Committee for Alpha Theory (www.

Copyright National Academy of Sciences. All rights reserved.

alphatheory.com), a portfolio management software company. He served on the board of directors of Lefthand Networks until the time of its purchase by Hewlett-Packard in November 2008. Mr. Blount spent 21 years on Wall Street, most recently with Lehman Brothers, where he was a leading analyst in multiple consumer and enterprise technology disciplines, including the Internet, wireless networks, PCs, servers, storage, hard drives, telecommunications, IT distribution, environmental services, and convertible securities. His weekly publication, *In Blount Terms*, was widely read by technology investors and executives. Prior to leaving Lehman Brothers in November 2007, Mr. Blount worked at a variety of firms, including Credit Suisse First Boston; Donaldson Lufkin & Jenrette; and CIBC Oppenheimer. Mr. Blount was named an All-American in Information Technology Hardware and Internet Infrastructure Services by *Institutional Investor* magazine. He was also recognized as a *Wall Street Journal* All-Star for Computer Hardware. From 2002 to 2006, while at Lehman Brothers, Mr. Blount served as an outside advisor to Nokia Innovent, a Nokia Ventures Organization company. Innovent evaluated emerging technologies for the digital home and data center. He has spoken at numerous events including Storage Visions, IDEMA (the Hard Disk Drive Industry Association), the Digital Home Developers Conference, and the Global Technology Distribution Council conference, and at internal management events at some of the world's leading technology companies. He appeared frequently on CNBC and the Bloomberg Report and has been quoted in numerous publications, including the *Wall Street Journal, Barrons, Forbes, Fortune*, and *Business Week*. Mr. Blount is a chartered financial analyst. He earned a bachelor's degree in finance from the University of Wisconsin at La Crosse in 1986.

Ruth David (NAE) is the president and chief executive officer of ANSER, an independent, not-for-profit, public service research institution that provides research and analytic support on national and transnational issues. In April 2004, ANSER was selected by the Department of Homeland Security to establish and operate a new federally funded research and development center, the Homeland Security Institute. From September 1995 to September 1998, Dr. David was deputy director for science and technology at the CIA. As technical advisor to the Director of Central Intelligence, she was responsible for research, development, and deployment of technologies in support of all phases of the intelligence process. She represented the CIA on numerous national committees and advisory bodies, including the National Science and Technology Council and the Committee on National Security. Previously, Dr. David served in several leadership positions at the Sandia National Laboratories, where she began her professional career in 1975. Most recently, she was director of advanced information technologies. From 1991 to 1994, Dr. David was director of the Development Testing Center that developed and operated a broad spectrum of full-scale engineering test facilities. Dr. David has also been an adjunct professor at the University of New Mexico. She has technical experience in digital and microprocessor-based system design, digital signal analysis, adaptive signal analysis, and system integration. Dr. David is a member of the Department of Homeland Security Advisory Council, the National Academy of Engineering (NAE), and the Corporation for the Charles Stark Draper Laboratory, Inc. She is chair of the National Research Council (NRC) Committee on Technology Insight—Gauge, Evaluate, and Review and vice chair of the HSAC Senior Advisory Committee of Academia and Policy Research. Dr. David received a B.S. degree in electrical engineering from Wichita State University, and an M.S. and a Ph.D. degree in electrical engineering from Stanford University.

Michele Gelfand is professor of organizational psychology at University of Maryland, College Park. Her research interests include cross-cultural social/organizational psychology; cultural influences on conflict, negotiation, justice, revenge, and leadership; discrimination and sexual harassment; and theory and method in assessing aspects of culture (individualism-collectivism; cultural tightness-looseness). She received her Ph.D. from the University of Illinois at Urbana-Champaign in 1996 and has been published in many top journals, including *The Academy of Management Review, The Academy of Management Journal, The Journal of Applied Psychology, The Journal of Personality and Social Psychology,* and *Organizational Behavior and Human Decision Processes*. She also recently published a chapter on cross-cultural organizational behavior in *The Annual Review of Psychology* with Miriam Erez and Zeynep Aycan.

Jennie S. Hwang (NAE) is CEO of H-Technologies and has had a wide-ranging career, encompassing international collaboration, corporate and entrepreneurial businesses, research management, technology transfer, and

Copyright National Academy of Sciences. All rights reserved.

global leadership positions, as well as corporate and university governance. Her work is highlighted by numerous national and international awards and honors, as well as distinguished alumni awards. Dr. Hwang was inducted into Women in Technology International Hall of Fame and named an *Industry Week* R&D Star to Watch. In her 30-year career, she has built new businesses in corporate America, having held senior executive positions with Lockheed Martin Corp., SCM Corp., Sherwin Williams Co., and co-founded entrepreneurial businesses. She is internationally recognized as a pioneer and long-standing leader in the fast-moving infrastructure development of electronics miniaturization and environment-friendly manufacturing. She is also an invited distinguished adjunct professor at the engineering school of Case Western Reserve University and has served on the University's board of trustees since 1996. Dr. Hwang is the holder of several patents and author of more than 300 publications; she is the sole author of several internationally used textbooks published by McGraw-Hill and other European and Japanese publishers. She is a columnist for the globally circulated trade magazines *Global Solar Technology* and *SMT*, where she addresses technology issues and global market thrusts, respectively. Additionally, she is a prolific author and speaker on education, workforce, and social and business issues. Over the years, she has taught over 25,000 researchers and engineers in professional development courses, focusing on disseminating new technologies and providing the professional advancement education to the workforce. Additionally, Dr. Hwang has served as a board director for Fortune 500 NYSE and NASDAQ-traded private companies and various university and civic boards. She has also served on the International Advisory Board of the Singapore Advanced Technology and Manufacturing Institute, among other international organizations. Her formal education includes a Ph.D. in materials science and engineering, two M.S. degrees in chemistry and liquid crystal science, respectively, and a B.S. in chemistry. She attended the Harvard Business School Executive Program.

Anthony Hyder is associate vice president for graduate studies and research and professor of physics at the University of Notre Dame. Dr. Hyder's research is in the interaction of spacecraft with the space environment. His recent work has focused on the design of spacecraft systems, especially the electrical power and thermal management subsystems, and on the operation of high-sensitivity infrared sensors aboard spacecraft. He has also worked in the physics of high-brightness particle accelerators. He has been appointed to a number of national and international panels and advisory boards, including the NATO sensors panel, the Defense Intelligence Agency scientific advisory board, the advisory board for the Missile Defense Agency, and the Army Science Board. Dr. Hyder is a graduate of Notre Dame with a B.S. in physics. He holds an M.S. in space physics and a Ph.D. in nuclear physics from the Air Force Institute of Technology (AFIT). He received the AFIT distinguished alumnus title in 2005.

Fred Lybrand is vice president, North America, for Elmarco, an equipment provider for the industrial-scale production of nanofibers, where he is responsible for new markets and sales and production strategy. He has transitioned between the finance and technology sectors several times. He raised and invested $2 billion into private equity and venture capital funds on behalf of state pension plans with Parish Capital, managed sales and business development with a private-equity-backed semiconductor manufacturer, and financed a number of midmarket and seed-stage transactions as part of Wachovia Securities. Mr. Lybrand holds an undergraduate degree in biology from the University of Virginia, an M.B.A. from the University of North Carolina, and the CFA and LIFA charters.

Peter Schwartz is cofounder and chairman of Global Business Network, a partner of the Monitor Group, which is a family of professional services firms devoted to enhancing client competitiveness. An internationally renowned futurist and business strategist, Mr. Schwartz specializes in scenario planning and works with corporations, governments, and institutions to create alternative perspectives of the future and develop robust strategies for a changing and uncertain world. His current research and scenario work encompasses energy resources and the environment, technology, telecommunications, media and entertainment, aerospace, and national security. Mr. Schwartz is also a member of the Council on Foreign Relations and a member of the board of trustees of the Santa Fe Institute, the Long Now Foundation, the World Affairs Council, and Human Rights Watch. He is the author of *Inevitable Surprises*, a provocative look at the dynamic forces at play in the world today and their implications for business and society. His first book, *The Art of the Long View,* is considered a seminal publication on scenario planning and has been translated into multiple languages. He is also a co-author of *The Long Boom*, *When Good Compa-*

Copyright National Academy of Sciences. All rights reserved.

nies Do Bad Things, and *China's Futures*. He publishes and lectures widely and served as a script consultant on the films "The Minority Report," "Deep Impact," "Sneakers," and "War Games." Mr. Schwartz received a B.S. in aeronautical engineering and astronautics from Rensselaer Polytechnic Institute.

Nathan Siegel is a senior member of the technical staff at Sandia National Laboratories. He received a B.S. in mechanical engineering in 1998 from the California State and Polytechnic Institute at San Luis Obispo. He attended San Diego State University from 1998 until 2000, graduating with an M.S. in mechanical engineering. During this time he was employed at General Atomics in La Jolla and worked in the field of inertial confinement fusion energy, the subject of his master's thesis. He attended Virginia Tech from 2000 until 2004, when he graduated with a Ph.D. in mechanical engineering. Dr. Siegel's research at Virginia Tech focused on the development and validation of advanced computational models of proton exchange membrane (PEM) fuel cells. He has been employed at Sandia National Laboratories since graduating from Virginia Tech. His research activities focus on solar interfaces for high-temperature hydrogen-producing thermochemical (TC) cycles and on the experimental validation of novel TC cycles. He has also recently been involved in PEM fuel cell research using neutron radiography to study two-phase flow within an operating fuel cell.

Alfonso Velosa III graduated from Columbia University with a B.S. in materials science engineering, from Rensselaer Polytechnic Institute with an M.S. in materials science engineering, and from Thunderbird, the Garvin School of International Management, with an M.I.M. in international management. Mr. Velosa is currently research director for semiconductors at Gartner. In this position, he focuses on semiconductor supply chain research, with a particular focus on global manufacturing and the semiconductor consumption trends of electronic equipment manufacturers. Mr. Velosa previously worked for or consulted to Intel, NASA Langley and NASA headquarters, Mars & Co., and IBM Research.

Copyright National Academy of Sciences. All rights reserved.

Appendix B

Meetings and Speakers

MEETING 1

October 15-16, 2007
Keck Center of the National Academies
Washington, D.C.

X2 Program
Marina Gorbis, Institute for the Future
Mike Love, Institute for the Future
Matt Daniels, Institute for the Future

Globalization of Technology: Impact on Defense S&T Planning
Alan Shaffer, Plans and Programs Office of the Director, Defense Research and Engineering

Technology Forecasting
Steven D. Thompson, Defense Intelligence Agency

Delta (S&T) Scan: Uses in U.K. Government
Harry Woodroof, Horizon Scanning Centre, Government Office for Science, Dept. for Innovation, United Kingdom

Copyright National Academy of Sciences. All rights reserved.

MEETING 2

February 26-27, 2008
Beckman Center of the National Academies
Irvine, California

Technology Forecasting and Long Term S&T Planning
Adam Nucci, Defense Research and Engineering

Adaptivity in a Disruptive World
Jeffery Hersh, Booz Allen Hamilton

Anticipating Future Disruptive Technologies
Jae Engelbrecht, Toffler Associates
Deb Westphal, Toffler Associates

International Forecasting
Peter Schwartz, Global Business Network

Search and Research: Bringing Science Onto the Web
Mark Kaganovich, Labmeeting, Inc.

Prediction Market Overview: Effectiveness in Forecasting Disruptive Technological Change
Russell Andersson, HedgeStreet Exchange

X2 Framework
Marina Gorbis, Institute for the Future
Mike Love, Institute for the Future
Matt Daniels, Institute for the Future

Processes and Strategies that Affect Commercialization Success
David Pratt, M-CAM, Inc.

The Global Technology Revolution 2020: Trends, Drivers, Barriers, and Social Implications
Philip Anton, RAND Corporation
Richard Silberglitt, RAND Corporation

X2: Threats, Opportunities, and Advances in Science & Technology
Alex Pang, Institute for the Future
Matt Daniels, Institute for the Future

Copyright National Academy of Sciences. All rights reserved.

MEETING 3

May 28-29, 2008
Keck Center of the National Academies
Washington, D.C.

Are Patents Useful for Predicting Important Technologies?
Paul Henderson, Clarify LLC

Disruptive Technologies Systems Approach
Gil Decker, Independent Consultant

Complex Digital Systems in the Knowledge Economy: Some Key Grand Challenges
Irving Wladawsky-Berger, IBM Academy of Technology

X2: Threats, Opportunities, and Advances in Science & Technology
Alex Pang, Institute for the Future
Matt Daniels, Institute for the Future

Scalable Text Mining
V.S. Subrahmanian, University of Maryland

Macro Trends and Related Technologies of Disruption
Jeff Jonas, IBM Entity Analytics

Online Research/Technology Forecasting Systems: Highlights of the TechCast Project
William Halal, George Washington University

Copyright National Academy of Sciences. All rights reserved.

Copyright National Academy of Sciences. All rights reserved.