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Forecasting the Technology Revolution: Results and learnings from the TechCast Project

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ABSTRACT

This research report presents latest results on the TechCast Project, first reported in Technology Forecasting & Social Change 14 years ago [1]. TechCast is an online Delphi system that pools background trends and the judgment of experts around the world to forecast breakthroughs in all fields. Results are presented for strategic technological advances that are likely to enter the mainstream and their expected impacts, providing an overview of the Technology Revolution. Aggregating the forecast data then provides macro-forecasts of broad timetables for economic and social change. This analysis suggests that the global economy is likely to enter a new economic upcycle about 2015 and reach an advanced stage of development about 2020. We also examine examples of how organizations develop technology strategy to compete in an era of economic transformation, and conclude by analyzing the role of forecasting as one of many methods for reducing uncertainty.

1. Introduction

This journal (TFSC) published the first results of the TechCast Project in 1998 [1]. Using a Delphi Method [2], forecasts were presented of the year when 85 emerging technologies are likely to enter mainstream use, along with estimates for probability, market demand, and leading nations. With early signs underway of a wave of rapidly emerging new technologies, the project was intended to map the full range of what is now often called the Technology Revolution. History has seen a series of "technology revolutions" – the Agrarian Revolution, Industrial Revolution, Information Revolution – but they can all be considered part of a single global transition that has been unfolding for thousands of years and is now accelerating very rapidly, as notably seen in popular views of a coming Singularity [3]. The goals of this project were defined as follows:

1. Apply advanced foresight and forecasting methods to estimate the arrival and impact of strategic technologies in all fields on a continuing basis.
2. Conduct validation studies to estimate the accuracy of the forecasts and to consider how they can be improved.
3. Study actual cases of technological innovation to better understand the role of forecasting and other methods for introducing new products and industries.

Today, this project has become a far more sophisticated system for the continuous tracking of strategic technologies. A special aspect of this work is that results are analyzed annually to estimate errors over the 20 years this data has been collected. Some of the original forecasts are uncanny in their accuracy, with many arriving quite close to the dates forecast in 1993. Note that forecasts are meaningless unless the level of adoption is specified, and these figures are usually for the 30% adoption level where technology enters the mainstream in industrialized nations.

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The arrival of "Broadband" was estimated at 2009, and actually entered mainstream use about 2008 in advanced nations. "Electronic Banking" was expected to become common by 2009 and reached 30% adoption globally at that exact year. We forecast most sea food would be produced using "Aquaculture" in 2014 and data confirms 50% adoption in 2012.

Another interesting finding is what could be called "forecast creep" — the much discussed tendency of experts to be overly optimistic in their estimates of when technologies mature. The early forecasts in 1993, for instance, estimated that TeleMedicine would be common by 2001, "Virtual Education" about 2003, and "Optical Computing" by 2007 — all now seen as demonstrably over-optimistic.

These examples highlight the strengths and weaknesses of the Delphi technique [4]. In the Research method section of this paper, we report validation studies suggesting an average error band of about +3/−1 years for forecasts ten years distant.

Prominent cases illustrate vividly the relentless disruption of the Technology Revolution in the rushing change of everyday products. When digital photography became feasible a few years ago, the film industry was overturned by digital cameras. Nikon, Kodak, and other famous names that once dominated photography struggled to adjust, laying off thousands of employees and replacing product lines. Kodak was forced to declare bankruptcy in 2012 [5].

New industries soon sprung up as digital cameras unleashed floods of photos and videos to populate Web 2.0 — Facebook, YouTube, blogs, wikis, and more sure to come. In turn, digital cameras are being replaced now by smart phones with built-in cameras. Ironically, Kodak invented the digital camera years ago, but abandoned the market to smart phones [6].

The same forces of technological change are at work as alternative energy replaces oil, genetic medicine extends lives, artificial intelligence automates jobs, robots serve as helpers, and other innovations reach the take-off point. Individuals and organizations are continually threatened by the failure to adapt to strategic technological change, but they also have unparalleled opportunities at the leading edge. And shorter technology life cycles require that managers act quickly or lose product lines. The only safe haven is to remain at the forefront of change.

The global recession that began in 2008 poses obstacles, of course, but technological progress is often insulated from economic cycles because R&D projects enjoy long-term support from governments, foundations, and universities. Entrepreneurs may delay product launches during recessions, but they also tend to discount downturns in favor of long-term prospects fueled by pent-up demand. In the depths of the Great Recession of 2008, we saw the success of Apple, Facebook, Twitter, Groupon, NetFlix, cloud, and mobile everything. Andy Grove, Chairman of Intel, put it best: "Technology always wins in the end."

All organizations are being affected as the forces of creative destruction erode core business sectors and open up new sources of value creation. The Internet continues to transform government, the newspaper industry, book publishing, entertainment, banking, education, health care, and other sectors. As consumption patterns, lifestyles, and even the rules of competition shift, business and other institutions face this common challenge of redefining goals, cultivating new markets, launching new products and services, and changing how their organizations work.

2. Forecasting the Technology Revolution

Based at George Washington University, the TechCast Project uses a data-based website (www.TechCast.org) to pool the knowledge of roughly 130 high-tech CEOs, scientists and engineers, academics, consultants, futurists, and other experts worldwide to forecast breakthroughs in all fields. The TechCast Team constantly scans to define adoption levels, driving trends, opposing forces, and other background information on each technology, thereby providing a significant improvement in the Delphi Method. We also conduct strategic studies for corporations and governments, which provides practical understanding of forecasting and strategy formulation at the leading edge.

2.1. Research method

Because TechCast is basically a system for aggregating knowledge, the fields of Knowledge Management and Collective Intelligence offer useful perspectives for understanding the rationale underlying this approach. From such views, this is an online "learning system" conducted by a "community of practice" that "continually improves" its knowledge using "collective intelligence" to approach a "scientific consensus." One of our most vivid experiences is seeing how pooling the tacit knowledge and collective intelligence of 130 good minds can create forecasts that are remarkably prescient.

Unlike most Delphi surveys, this work strives to become more science-based and less speculative because it draws on empirical data for each technology to guide expert judgments. Editors gather information on research progress underway, commercial ventures, adoption levels, and other relevant facts, which are organized into a succinct analysis of trends driving each technology. We make a point of including opposing trends that hinder development, such as political obstacles, high costs, or social resistance, to ensure that the analysis is balanced.

Experts are taken through these analyses online and instructed to integrate the background data and their judgment to estimate when each technology is most likely to enter the mainstream, the potential size of the economic market, and their confidence in the forecast. The experts are not all world-renowned, but they represent the leading edge of knowledge on technology. Experts self-select areas they know best, so sample sizes average about 50–70 responses. The raw data is automatically aggregated for distribution to clients over the site in real time.

More than snapshots in time, this is a continual tracking process that improves as comments from the experts and new data update the analyses periodically. Annual validation studies find that the average variance of all forecasts is roughly +3/−1 years at ten year horizons. Complex technologies vary widely because they are controversial, while others that are more simple show little variance and are well understood. We have also recorded arrivals of several technologies roughly within this same error band.

The results are compelling when considering the fact that the expert panel changed over this time, as did the prospects for various technologies and other conditions. "Prediction markets" have demonstrated sound accuracy using a similar form of collective intelligence [7]. This work also holds up well in our work for corporations and governments. On one consulting assignment, we conducted two parallel studies to forecast the maturing of energy technologies, one using a group of energy experts and the other using a group of general experts. The forecasts compared almost exactly, usually within one to two years [8].

It is often thought that methods like this are subjective, whereas quantitative methods are precise. However, quantitative methods also involve uncertainty because they require underlying assumptions that often are doubtful, and so they can vary widely. This approach subsumes quantitative forecasts into the background data and allows the judgment of experts to resolve the uncertainty that remains. Experts may have their own bias, naturally, but it is usually distributed normally, washing out in the aggregate results. If the present level of uncertainty is defined as 100%, we have found that this process reduces uncertainty to about 20 to 30%.

2.2. Results: mapping technology breakthroughs

The results show that technological advances, their adoption patterns, and social impacts follow well-defined cycles that can be forecast rather accurately. Fig. 1 presents highlights of this work for 70 leading technologies organized into seven fields. Some of these technologies are available commercially but they have not yet reached the 30% adoption level where breakthroughs enter mainstream use. Following is a quick summary of how these advances are likely to affect various business sectors. Please note that these highlights are drawn from the website, and so details and references can be found at www.TechCast.org.

2.2.1. The energy & environment crisis is an opportunity in disguise

Globalization is expected to almost double the number of people living at industrial levels over the next decade or two [9], producing commensurate increases in energy demands, pollution levels, and global warming [10]. Our forecasts show that green business is likely to take off at about 2020 and governments are likely to take serious steps on global warming about that time. Alternative energy sources – solar cells, wind turbines, biofuels, etc. – are growing 30–40% per year, almost like Moore's Law. The global market for green technologies is expected to reach about $10 trillion USD in two–three decades, larger than autos, health care, or defense. In short, the energy and environment mess offers a great opportunity in disguise.

2.2.2. Information technology changes everything

Computer power should continue to double every two years; a second generation of optical, biological, and quantum

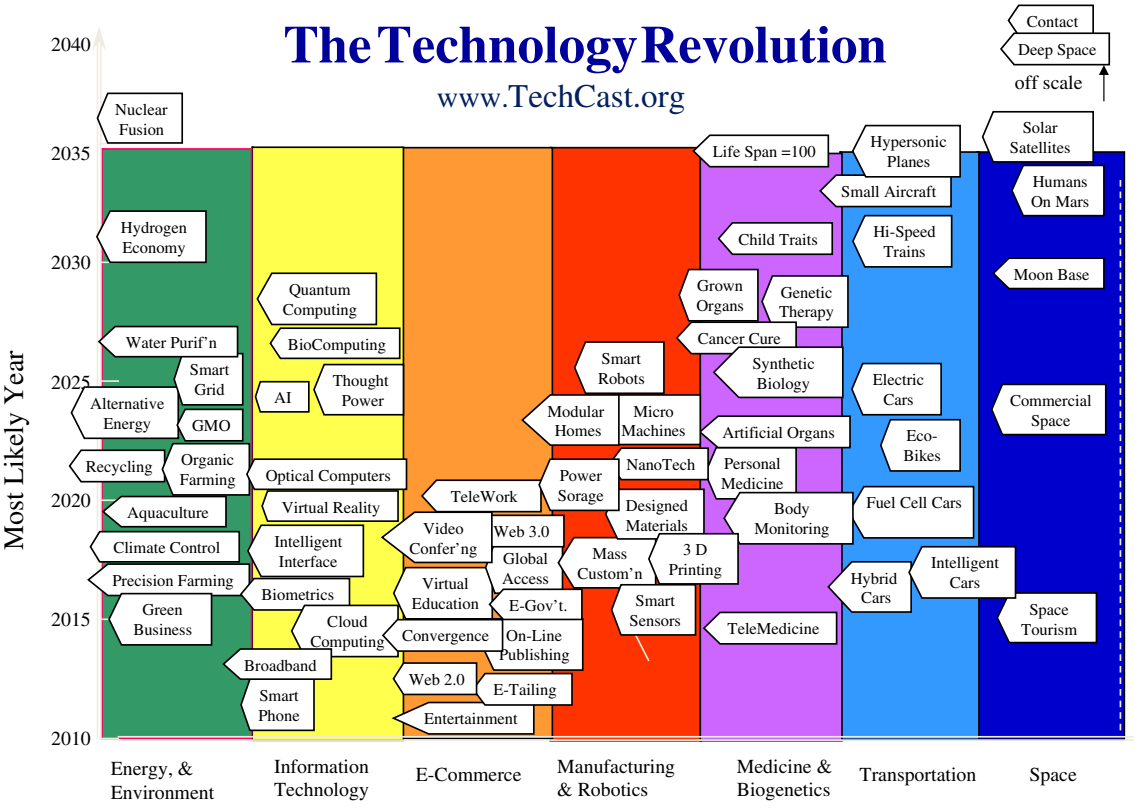

Fig. 1. The technology revolution.

computers is poised to take over; and artificial intelligence is automating routine tasks. The Web is the same age that TV was when it became the dominant force of the 20th century. Over the coming decade, working, shopping, learning, and most other social functions are likely to move online into a virtual world that is ever-present and intelligent. You might buy something by simply talking with a virtual robot that greets you by name, knows all the merchandise and displays it on demand, answers questions, and has infinite patience — the perfect salesperson [11].

2.2.3. E-commerce is exploding around the globe

Most e-commerce today operates at 10–15% adoption levels, but online shopping, publishing, education, entertainment, and other services are likely to reach the critical 30% adoption level soon where new markets usually take off. And the huge populations of China, India, Brazil, and other developing countries are moving in droves to PCs, the Internet, and smart phones. We anticipate that five–six billion people will soon create online markets of several trillion dollars. C.K. Prahalad, a former business professor, put it best: "The world's four billion poor should be considered the biggest source of growth left" [12].

2.2.4. Manufacturing goes high-tech

The factories of the Industrial Age are yielding to intelligent manufacturing systems operating worldwide to produce goods cheaply and quickly. Research in materials and nanotechnology is making it possible to create almost any type of product, and mass customization can deliver sophisticated goods designed for individuals easily. Attracted by cheap labor and new markets, industrialization is likely to raise living standards dramatically in most poor nations over the next few decades — along with mounting demands for energy, ecological damage, and clashes between diverse cultures. An industrialized world will be a boon to business, but making it sustainable is an enormous challenge that will test us severely.

2.2.5. Medical advances confer mastery over life

Artificial organs are being developed to replace almost all bodily functions, including parts of the brain, and stem cell research is increasingly able to repair and grow organs. Electronic medical records, online doctor's visits, computerized diagnostics, and other forms of telemedicine should curtail rising costs and improve quality of care. Nanotech is being used to develop tiny devices that are intelligent enough to seek out cancer cells and destroy them. Just as the Industrial Age mastered most aspects of the physical world, these advances are now making it possible to master the biological world. Yes, it sounds too good to be true, but so did the notion that men could fly, much less to the Moon.

2.2.6. Transportation is moving faster and farther

Our forecasts show that a new wave of green autos powered by hybrid, electric, and fuel cell engines should become mainstream about 2013–2018, and we are likely to see intelligent cars that drive themselves. It may seem that information systems could replace travel, but information forms a virtual world that parallels the physical world. People will always want to visit each other, handle the merchandise, and hammer out tough decisions together.

2.2.7. Space is going private

CEO Richard Branson's Virgin Galactic is likely to launch its first suborbital flight of tourists about 2014, commercial spacecraft are servicing the International Space Station, and other competitors are planning visits to the Moon and space hotels. Just a few years ago the idea seemed laughable, but it now looks like space commercialization will soon open the final frontier to private ventures [13]. As access to space becomes widely available, it's easy to imagine how this watershed from government control to private enterprise could unleash a rush of space pioneering.

2.3. The next economic upcycle

Our collective forecasts can also be aggregated to "macro-forecast" the global economy over the next decade or two. The bubble chart in Fig. 2 presents all three dimensions of all forecast data: Most Likely Year, potential Market Size, and Experts' Confidence. This analysis suggests that the Great Recession may linger for a few years, but a new wave of economic growth is likely to take off about 2015.

The period around 2015 is significant because the cluster of green technologies, information systems, e-commerce, and advanced auto designs in Fig. 2 suggests that a resurgence of economic growth is likely about that time. This also coincides with the pattern of 35 year cycles that roughly govern U.S. stock markets. A 100 year graph of the Dow Jones Industrial Average on a log scale will show distinct 35 year cycles. The Roaring Twenties was the peak of a 35 year cycle that ended with the Great Crash of 1929. The Eisenhower boom of the sixties started about 1945 and was followed by the Reagan boom that began with his election in 1980. The 2008 economic crisis marked the end of the Reagan 35 year cycle, and it is likely be followed by a new worldwide boom starting about 2015 based on the technologies noted above.

TechCast also studies various critical issues that cut across all technologies, and our study on the Global MegaCrisis [10] is sobering. The Great Recession that began in 2008 soon escalated into a common concern over interlocking forces of climate change, energy, financial instability, water, cyberwarfare, and other yet unforeseen threats. As Table 2 shows, our survey data suggest a 60% probability that major parts of the globe will suffer the loss of civilization or enter a high-tech dark age (first two scenarios). People the world over have deep anxiety over entrenched failures in governance, and they do not see a way through this impasse. Futurist John Petersen calls it "the greatest challenge and disruption in our history [14]." Following is a summary of our survey that estimated the probability of alternative passages through the MegaCrisis. Details are in [10].

The MegaCrisis is likely to reach intolerable levels as global GDP doubles in the next decade or so, increasing all these threats proportionately and seizing mounting attention. Although the situation looks bleak, that always seems the case at major turning points, and history shows that the long evolution of civilization usually overcomes the threats — the Fall of Rome, the Dark Ages, World Wars I and II, the cold nuclear war, etc. In a similar way, our forecasts suggest the

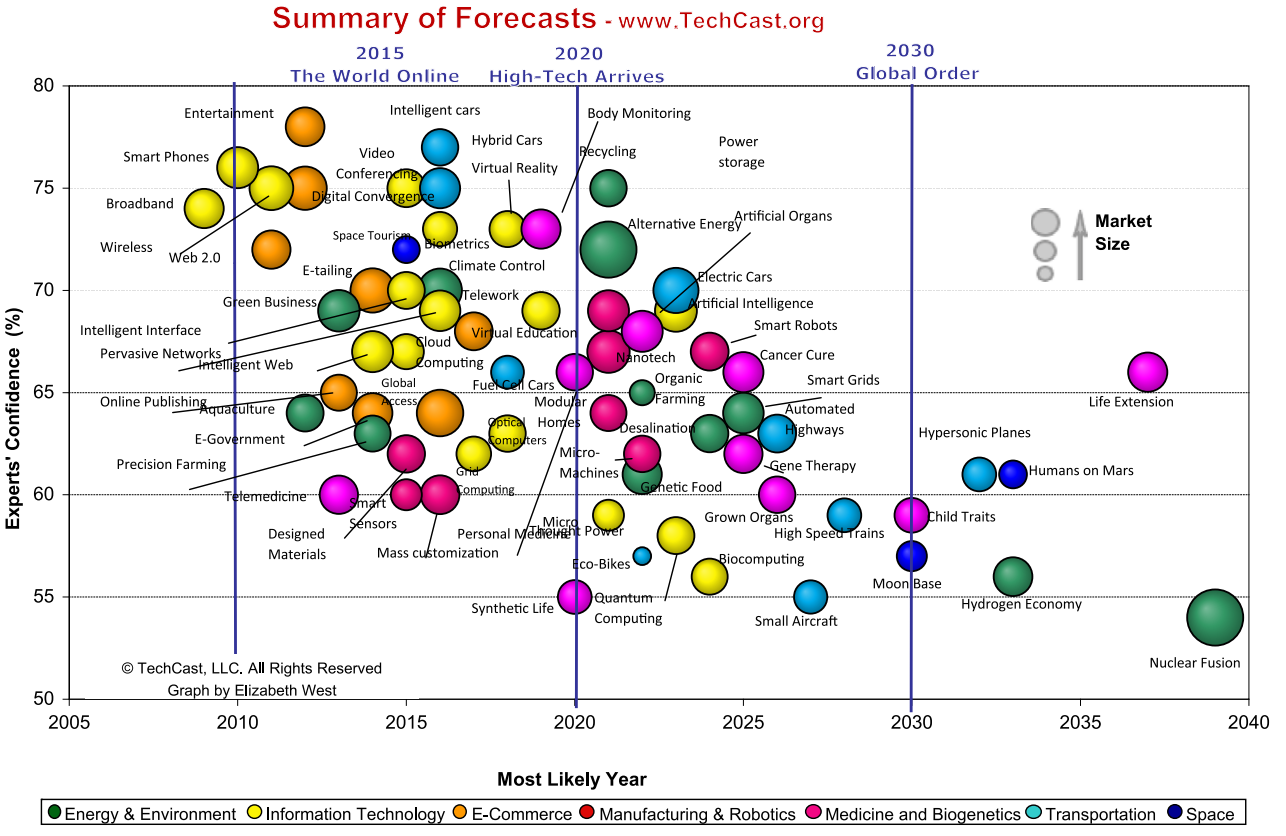

Fig. 2. Summary of forecasts.

MegaCrisis could be resolved by the following summary of major advances along the lines of the Muddling Up scenario.

As the Technology Revolution picks up speed about 2020, our expert panel collectively thinks we are likely to see widespread use of green technology, alternative energy, a connected global middle class, hi-tech medicine, intelligent cars, and the other advanced technologies shown. We are also likely to enjoy near-infinite computing power with 2nd-generation architectures (optical, bio, nano, quantum). Smart robots are likely to enter homes and offices, and good AI is likely to automate routine tasks, in the same way GPS navigation solved the problem of traveling from point A to point B.

3. Technology strategy in action

We now draw on prominent corporate exemplars – NetFlix, Apple, and Toyota – as well as our consulting work

Table 1
Managing uncertainty.

	Type of uncertainty	Simple Delphi	TechCast system	Present Value	Decision trees	Real options
Total uncertainty	*Subjective uncertainty reduction* Information chosen to define problems and apply methods.	• Select targets. • Frame forecasts. • Interpret results & comments	• Select targets. • Frame forecasts. • Interpret results & comments	• Select discount rates • Estimate costs and gains over time	• Define outcomes and payoffs • Estimate probabilities	• Define options and payoffs • Select Decision points
	Objective uncertainty reduction Information calculated within a method to reduce risk.	• Calculate means and distribution • Iterations	• Calculate means and distribution • Iterations • Obtain empirical data. • Conduct annual validation	• Calculate present value	• Calculate expected value	Calculate investment value
	Unknowns	• Surprises • Failures • Windfalls				

Table 2
TechCast survey on the MegaCrisis. (Results as of June 10, 2012. Sample = 55).

Decline to disaster — 25% probability. World fails to react. Global warming, sea level rise, energy shortages, economic depression, nuclear exchange, etc. Catastrophic loss of civilization in major nations.
Muddling down — 35% probability. Weak response. High-tech dark age, ecological damage, increased poverty and conflict.
Muddling up — 28% probability. World reacts out of need and the help of IT/AI. Disaster avoided but some increased disorder
Rise to maturity — 12% probability. Ideal transition to a responsible global order.

to illustrate patterns or themes in the diverse ways successful managers conduct technology strategy [15].

3.1. Tracking strategic technologies and social trends

Organizations are affected by different technologies and trends, so it's essential to monitor those that are strategic for a specific organization.

The crucial technologies affecting NetFlix revolved about widespread adoption of broadband and compression techniques that enable streaming video. A critical threshold occurred in 2005 when 30% of American homes gained broadband. YouTube was launched and its instant success dramatically signaled that the take-off point in streaming video had arrived. Today, video comprises roughly 90% of all Internet traffic and is expected to reach 3.5 billion viewers by 2015 — a huge new market hungry for movies, TV, and other digital entertainment that NetFlix now serves with online customer service and a virtual organization [16].

Likewise, Apple had to anticipate a wave of creative new technologies to make the IPod, IPhone, and IPad possible — more computer power and memory, good wireless systems, and the intuitive feel of those lovely touch interfaces. Toyota had to track the development of high-performance lithium-ion batteries and hybrid technology, as well as the coming of Peak Oil and public concerns over the environment.

Toyota began planning their game-changing hybrid, the Prius, in 1970 because forecasts indicated a decline in oil supplies and growing public concern over the environment. The obstacles were great because batteries were not adequate, hybrid technology would take many years to develop, and product costs would remain high. But their forecasts showed the obstacles could be overcome, and the demand for green autos looked promising. Toyota's executive vice president, Masatami Takimoto, handled the uncertainty of such radical innovation by pursuing competing hybrid technologies and then choosing the one that works best — the Prius [17].

As noted in the Introduction, we forecast growing business opportunities in aquaculture quite accurately, mainly because it was clear that rising demand for the health benefits of eating fish was outstripping supply. The world's catch of wild fish topped out in 1985, and many species could become extinct soon. The rise of aquaculture parallels the rise of chicken farming, and is now growing three times the rate of meat production.

These cases highlight the central need to track strategic technologies and reduce uncertainty in corporate strategy. The variations are endless, but organizations need to scan for trends, forecast breakthroughs, and plan for technological and social change. It's also crucial that implementation plans be timed quite precisely. Taking such big risks as NetFlix, Apple, and Toyota did a few years too early would invite bleeding-edge failures, while a few years later the field would be left to competitors.

3.2. Developing creative opportunities

Trends have to be explored carefully to discover creative opportunities for converting disruptive breakthroughs into successful ventures.

Possibly the best example is the brilliant way Steve Jobs used advanced technologies to create stunning new products that transformed computers, music, telephones, tablets, and even retail stores. Here's how he described the IPad — "It's like holding the Internet in your hands; so much more intimate than a laptop and more capable than an iPhone. Truly magical [18]."

Jobs didn't focus on market research because he was planning transformative products that few understood. Success requires "listening to the technology," he said, in order to "discover" the potential products waiting to be invented [19]. "If I had asked someone who only used a calculator what a Mac should be like, they couldn't have told me. There's no way to do consumer research so I had to go and create it, and then show it to them… It's not the customer's job to know what they want." [19].

NetFlix also illustrates the central role that an inspired vision plays in transforming a field. The CEO, Reed Hastings, is a Stanford computer scientist and a Silicon Valley entrepreneur, so he knew it would soon be feasible to stream movies, and that this shift in technology would change the rules of the game. When YouTube and other Web 2.0 sites erupted on the scene, Hastings realized the time has come to cannibalize the DVD rental business in favor of streaming video. He also knew that having employees run shops, charging for rentals, and imposing late fees were outmoded relics of the past, while online service delivered flawlessly by a virtual organization offered unbeatable value. John Doerr, a partner at the venture capital firm Kleiner Perkins, said "Reed was ahead of the technology curve, and completely changed the industry".

Toyota's Prius not only anticipated these trends, its leaders were inspired by a radical vision of green transportation. While GM, Ford, and other car companies procrastinated, Toyota executives had the foresight to envision a new generation of hybrid cars that were energy efficient and non-polluting. In 2010, Toyota surpassed GM as the world's biggest car maker [20].

Countless other examples could be cited illustrating the value of an inspiring purpose and vision in converting trends into bold possibilities. Nothing reduces uncertainty like knowing where the organization is going and how to get there.

3.3. Making collaboration productive

Leading companies collaborate because the knowledge, ideas, and commitment gained by working with employees, partners, clients, and other stakeholders can be productive. Social responsibility and ethics are commendable, but it takes active collaboration to actually resolve tough challenges and create value [21].

Steve Jobs created a political breakthrough in entertainment by convincing the record companies that the future lay in online music sold for $ 0.99 USD per song. Hastings had to create a collaborative ecosystem of media companies, Internet firms, talented staff, and viewers to make streaming video a reality.

Toyota offers an instructive negative example because insular management was largely responsible for the damage caused by runaway cars that required millions of recalls and shredded the company's reputation. A study by the U.S. Department of Transportation found that Toyota management "gave too little weight to feedback from customers, regulators, and rating agencies, and centered too much control in Japanese headquarters [22]."

The power of cooperation is clear in our consulting work. A project for the Federal Drug Administration to assess the prospects for medical advances used a panel of experts drawn from the National Institutes of Health, the National Science Foundation, the Department of Commerce, and pharmaceutical and biotech companies. Results were presented for discussion at a conference that included all these stakeholders, offering one of the first serious opportunities to coordinate strategies for health care development across the nation.

Today, the US Agency for Health Research and Quality (AHRQ) and similar government programs in the UK, Spain, Austria, Canada, Australia, and New Zealand are all forecasting medical technologies because the Technology Revolution is transforming medicine, and health care providers are struggling to adapt. They are now pooling their knowledge in an online repository to avoid redundant work, making better results available around the world far more quickly and cheaply.

3.4. The important role of failures

The great uncertainty of disruptive technologies invites failures, but failure can teach valuable lessons. Much like the knowledge that one is to hang in the morning, a good disaster can clarify the mind wonderfully.

NetFlix tried to develop a TV set-top box for streaming movies, but it flopped because of 16 h of download time. This failure led to the realization that an open-source approach offers far greater advantages. By distributing movies via TVs, DVD players, desk-top computers, mobile phones or almost any device, NetFlix was freed of the responsibility for producing hardware and able to focus on its core competence of managing an online movie library.

The most striking thing about Apple's rise is that Steve Jobs learned crucial lessons from failure. After years of his autocratic leadership, dismal sales, and temperamental behavior demoralized the company, John Sculley became CEO in 1985 and Jobs was sent into the computing wilderness. When he returned to head Apple in 1997, Tim Bahrain, who heads a consulting firm, said "Steve would not have been successful if he hadn't gone through his wilderness experience [23]."

Hedging is often used to distribute the risk of failure. Toyota is hedging on the rise of electric cars by developing plug-in hybrids, working on advanced batteries, investing in the electric car start-up (Tesla), and developing its own all-electric. A Toyota spokesperson explained the strategy: "Customers are going to ultimately decide what kind of car they want. Whatever they choose, we will be there." [17].

We assisted a major organization in planning a high-tech industrial park that included more than 30 technologies. The most promising technologies were selected based on forecasts, and choices were also guided by portfolio management methods. The ventures that prove disappointing are offset by those that succeed to realize sound overall return rates for the project as a whole.

4. Discussion and conclusions

The above examples illustrate the importance of good forecasting, but they also illustrate that forecasting is but one method intended to aid decision-makers in their central challenge of reducing uncertainty. Some prominent methods that also reduce uncertainty in the strategy planning process include "Decision Trees," "Present Value," "Real Options," and many other approaches used to inform and reach decisions.

Below is an analysis of TechCast's accuracy and the typical "goofs" any system encounters. Then we will compare this analysis with other methods for reducing uncertainty, and conclude with recommendations.

4.1. TechCast accuracy and goofs

The most recent round of annual validation studies in 2012 show little change in forecast dates generally, which is good because accurate forecasts remain valid and constant over time. We notice a continuation of the same $+3/-1$ years average error band at about 10 years out. Good longitudinal forecast data series are rare [24], so the TechCast data offers interesting research opportunities.

We also notice the same tendency toward optimism — what we call "forecast creep." Some technologies involving great uncertainty seem to lose a year or two every so often in their life cycle, and our forecasts reflect that sometimes by creeping slowly into the future. How much is due to inherent uncertainty and unexpected obstacles versus poor knowledge and judgment of experts is a good question.

TechCast deals with error by improving transparency. Accuracy results are made widely available and experts encouraged to incorporate them into their estimates. To create a sound system of collective intelligence, it is necessary to learn and improve with mistakes. All systems fail at times, and good systems learn from their failures. For this same reason, here are three goofs we noticed recently.

4.1.1. Aquaculture

Our expert panel said Aquaculture would not reach the 50% adoption level until 2014, and a few entered estimates of 2050 — even though the Selected Adoption and Forecast Data (SAFD) notes it reached 47% in 2009. Recent data suggests the 50% target was reached this year – 2012 – two years before our estimate. We queried the outlying experts and they acknowledge it was an oversight. Despite this error, however, original forecasts of 2014 proved pretty valid over almost 20 years, which highlights the robust nature of the data.

4.1.2. E-tailing

Our SAFD clearly show that current adoption is only about 8% yet the experts thought 30% will be reached by 2015. This errs in the other direction, but it also involves overlooking the data. We explored the problem more carefully, and a more basic issue is that e-tailing is likely to saturate at about 50%, so 30% is too ambitious a target. We changed the target to 15%, which is more like mainstream.

4.1.3. Life extension

TechCast experts forecast average life expectancy (LE) to reach 100 years about 2035 — until we noted this would be almost impossible mathematically. To raise LE to 100 years would require anti-aging remedies good enough to cause a huge number of people to live beyond 100. But only 1–2% of the global population will be old enough to exceed 100 years of age for decades. Because the LE index relies on deaths, it doesn't reflect the longer life spans of young people who will soon use the flood of medical advances forecast here. Many authorities think people as old as 50 today will live beyond 100 on average.

These errors are partially the result of poorly defined targets, and so the editors are constantly rethinking the event being forecast into a sharp and salient focus. But it is also true that some experts do not pay attention to the SAFD. Experts are instructed to use their knowledge and judgment to integrate trends, SAFD, present results, and any other sound knowledge into best possible estimates of where the technology is heading. This takes time to read and digest, of course, and some experts do not bother. Such goofs are the exception, however, as validation results confirm.

More generally, using an empirical base of background data grounds the forecast by reducing uncertainty and conducting a validation process opens up new areas for discovery and improvement. As just noted, going through an annual update and validation typically redefines forecast targets and expert practices to reduce error, producing a big improvement in the Delphi Method.

4.2. Comparing methods to reduce uncertainty

Table 1 maps out the type of information provided by various decision-making systems in order to better understand the role of forecasting vis-à-vis other approaches. Drawing on previous work [25], the total uncertainty can be organized into “Subjective” and “Objective” approaches to reducing uncertainty [26] and “Unknowns.”

This is admittedly a simple, preliminary analysis, but it demonstrates a few key points. First, it clarifies the advantages of TechCast's method over the typical “Simple Delphi.” Both require subjective judgment to select, frame, and interpret forecasts, and both use objective knowledge to calculate means and distributions of responses. TechCast reduces uncertainty beyond this level by using empirical background data and validating results to enhance the strengths of objective knowledge.

We can also see that all methods involve various assumptions about subjective forms of uncertainty. The methods in Table 1 may use objective calculations within well-defined models, but they all rest on a foundation of choices about how to frame problems, estimate risk and payoffs, and other forms of subjectivity. Some uncertainty always remains after the most rigorous methods are applied because all methods are limited, and there are always unknowns beyond available knowledge. That's why subjective judgment is always necessary ultimately in strategy formulation.

This analysis also illustrates that different methods are good at reducing different types of uncertainty. There are possibly hundreds of methods that focus on other aspects of a problem (scenarios, cross-impact maps, etc.), illustrating the many possible sources of uncertainty and approaches to resolving it. Depending on which type of uncertainty is critical, different methods are likely to prove useful, and combinations of methods are common.

4.3. Conclusions

This report has presented recent results from the TechCast Project first reported in 1998, and it demonstrates that the three study goals originally set for the project have been met reasonably well. High-quality forecasts of emerging technologies covering all fields have been made available for 15 years as of 2013. All forecasts can be wrong, of course, but this work confirms that it is possible to provide estimates accurate enough and of sufficient value to guide the strategy of decision-makers. This body of research has produced numerous publications, presentations, workshops, media attention, and consulting work. Validation studies have been conducted annually for the past several years, and corrective steps made to improve results. We have also studied the progress of progressive corporations introducing innovative products to understand the role forecasting plays in strategy formation.

We think it is fair to claim that this project is arguably among the best forecasting systems available, covering the entire range of technological innovation, updated constantly, validated annually, and improving continually. A report of the National Academies included TechCast as one of 3 leading exemplars of continuous forecasting [27], and web searches rank it No. 2 or 3 out of 105 million hits. The work has been featured in *The Washington Post*, *Newsweek*, *The Futurist*, academic journals, and other publications. And this large body of research continues to grow over the years, hopefully providing unusual insights to guide good forecasting practice, the role of technology forecasting, and directions for improvement.

For instance, the seventh generation of the website is planned for 2013, which will expand the scope beyond tech forecasts to include social trends and wild cards — thereby covering the entire organizational environment. A new Strategic Tools Service will provide analytical tools allowing clients to integrate technology forecasts, social trends, wild cards, and other external factors by selecting items to drop into a customized strategic plan. Decision-makers must still do the hard work of thinking strategically, of course. Tools serve as an organizing framework, or a platform for "automating" the heart of good strategy, hopefully making good forecasts and strategic planning widely available.

University faculty and students are invited to use the TechCast data for theses and dissertations. The annual validation study now comprises a large and unique

time-series knowledge base recording actual forecasting estimates over 20 years and growing. This data repository offers rare opportunities for further research on critical questions that require further study — Which experts prove to be more accurate and why? Can we predict expert profiles that produce more accurate forecasts? How accurate are forecasts at various time horizons — ten years out? Twenty years out? What causes the tendency toward optimism, or forecast creep?

With such bold changes and prospects likely over the next decades, it is essential to prepare for the Technology Revolution. Researchers, scholars, and practitioners badly need to develop more powerful forecasting systems to guide strategic change for what appears to be mounting wave of innovation and creative destruction. Whatever the method and whatever the purpose, the fact is that institutions need to develop some well-thought system to forecast and adapt to a profound transformation. There may be uncertainty about specific breakthroughs, but there is very little uncertainty that we are going to see an unusually disruptive wave of technological, economic, and social transformation over the planning horizon.

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References

[1] W. Halal, et al., The GW forecast of emerging technologies, Technol. Forecast. Soc. Chang. 59 (1998) 89–110.
[2] H. Linstone, M. Turoff, The Delphi Method, Addison-Wesley, London, 1975.
[3] R. Kurzweil, The Singularity is Near, Penguin Books, NY, 2005.
[4] G. Rowe, G. Wright, The Delphi Technique: Past, Present and Future Prospects, Tech. Forcasting Soc. Chang. 78 (9) (2011) 1487–1720.
[5] Michael J. de la Merced, Eastman Kodak Files for Bankruptcy, New York Times, January 19, 2012.
[6] D. Matattioli, Kodak shutters camera business, Wall Str. J. (February 10, 2012).
[7] J. Wolfers, E. Zitezwitz, Prediction markets, J. Econ. Perspect. 18 (2) (2004) 107–126.
[8] J. Laitner, Energy Impact of Emerging Technologies, Environmental Protection Agency, Washington, DC, 2004.
[9] International Monetary Fund, World Economic Outlook, International Monetary Fund, Washington, DC, 2012.
[10] W. Halal, M. Marien, Global MegaCrisis: a survey of four scenarios on a pessimism–optimism axis, J. Futur. Stud. 16 (2) (2011) 65–84.
[11] W. Halal, The intelligent internet, The Futurist, March–April 2004.
[12] C.K. Prahalad, The Fortune at the Bottom of the Pyramid, Pearson Prentice Hall, New York, 2006.
[13] Office of Space Commercialization, http://www.space.commerce.gov June 18, 2012.
[14] J. Peterson, A Vision for 2012: Planning for Revolutionary Change, Fulcrum Publishing, Golden, CO, 2008.
[15] W. Halal, Business strategy for the technology revolution: competing at the edge of creative destruction, J. Knowl. Econ. 152 (October, 2012).
[16] Cisco: by 2013 Video Will Be 90 Percent of All Consumer IP Traffic and 64 Percent of Mobile, www.TechCrunch.com January 15, 2013.
[17] H. Tabuchi, Toyota Aims to Remain King of the Hybrids, Washington Post, January 7, 2011.
[18] S. Lohr, Steve Jobs and the Economics of Innovation, New York Times, January 31, 2010.
[19] BusinessWeek, Being Steve Jobs Boss, BusinessWeek, Oct 20, 2010.
[20] Consumer Reports, Car Brand Performance Survey, , 2011.
[21] Halal, The collaborative enterprise: a stakeholder model uniting profitability and responsibility, Corp. Citiz. 1 (2) (2001) 27–42.
[22] P. Whoriskey, Toyota Too Insular Before Recall, Washington Post, May 24, 2011.
[23] K. Lakhani, Google Wave Decision Shows Strong Innovation Management, www.HarvardBusinessReview.org August 6, 2010.
[24] R. Parente, J. Parente, A case study of long-term Delphi accuracy, Tech. Forcasting Soc. Chang. 78 (9) (2011) 1705–1711.
[25] T. Wang, Comparison of Methods for Valuating Technology Innovation and Adoption Projects, Unpublished Doctoral Dissertation, George Washington University, March 9, 2007.
[26] P. Tapio, et al., The Unholy Marriage? Integrating Qualitative and Quantitative Information in Delphi Processes, Tech Forecasting &amp, Social Change 78 (9) (2004) 1616–1628.
[27] National Research Council, Persistent Forecasting of Disruptive Technologies, National Academies Press, Washington, DC, 2010.

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