Crossroads 2014
Biomanufacturing, Robots, and 4-D Printing: The Next Decade of Disruptive Innovation

Summary Report

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Executive Summary

Crossroads 2014 focused on game-changing research, technology, and approaches that could potentially disrupt manufacturers and supply chains as well as other industries, including education.

The day began with Prof. Suzanne Berger reporting on MIT's Production in the Innovation Economy (PIE) research. Prof. Berger examined the innovation inputs (worker skills, capital, suppliers, learning, facilities and policies) required for commercializing new ideas and compared the performance of US startups and small-to-midsize manufacturing firms to their counterparts in Germany and China. Her findings showed that maintaining a high-wage economy does not always imply a loss of manufacturing jobs. The PIE research also highlights skills gaps in the US as well as shortfalls in financing options and other support mechanisms for commercializing innovations. These gaps could hurt the long-term health of the US economy.

Next, Prof. Sam Madden, Director of MIT's Big Data Initiative, described the latest approaches that enable fast, automated analysis of high volumes of multi-source data. The approaches decrease the human-intensive analysis processes, meaning that much more data can be analyzed, and it can be analyzed without the need for generating hypotheses about outcomes ahead of time, which makes it possible to find unanticipated insights.

Although highly-interconnected networks of devices provide companies with valuable data, they also present security vulnerabilities, as Dr. Abel Sanchez explained. The least-secure cell phone or network printer in an organization provides a backdoor for a major security breach. Dr. Sanchez delineated the weaknesses of current cyber security approaches and provided recommendations for best practices. He also discussed the results from four research projects in his lab that are enabling faster detection of cyber intrusions, fraud and malicious attacks.

Prof. Julie Shah posited a new robot age in which humans work collaboratively with robots on the factory floor. She described the current limits of industrial automation (namely, safety and quick reprogramming of robots) and offered solutions, including new scheduling algorithms that recalculate complex, multi-agent schedules in seconds by borrowing scheduling techniques used in managing real-time computers.

Skylar Tibbits, Director of the MIT Self-Assembly Lab, showed how smart materials can self-assemble into complex structures. With 4-D printing, parts can be programmed to change shape in response to the environment. Mr. Tibbits demonstrated how an easily-shipped flat part could automatically fold itself into a large complex structure when exposed to water. Bulky or delicate objects could be shipped in a compact state and then self-assembled at the customer site. Self-assembled and smart 4-D objects could change the need for assembly labor, the costs of shipping, and the versatility of manufactured products, thereby changing manufacturing practices and strategies.

The day ended with Prof. Sanjay Sarma discussing the transformation of education through online learning. MIT is co-developing the edX open platform that brings education to the masses while supporting the on-campus experience and facilitating supply chain management training with SCMx. Online education could help close the skills gap and retrain employees affected by disruptive innovation.

1. Future of Manufacturing and Innovation, Prof. Suzanne Berger, Director, MIT International Science & Technology Initiative

Prof. Berger began her presentation with a cartoon showing two executives looking into an empty factory. One executive says to the other, "Well, that does it Charlie, we've outsourced everything." The cartoon encapsulates the motivation for Prof. Berger's research: given that most US companies have outsourced manufacturing and so many other functions, what does the future of manufacturing and innovation look like in the US? Does the US even need manufacturing to derive full value out of its innovations, namely to create profitable, resilient companies and new jobs?

The US economy depends on getting innovation to market, but some great companies, such as Cisco, Apple and Qualcomm, do virtually no manufacturing while still reaping the lion's share of profits. So perhaps US companies can just do the research and design, and outsource everything else. In short, Prof. Berger's research project, Production in the Innovation Economy (PIE), aimed to answer the question: what kinds of manufacturing does the US need in order to reap the full benefits of its innovations?

1.1. Innovation Spectrum

Innovation is not just about patenting inventions. Rather, it covers a whole spectrum of activities, including radical innovation as well as efficiency gains, market expansion, customization, valuable niches, repurposing, and new business models. Indeed, manufacturing processes can be innovative, as evidenced by NASA deciding to tour P&G's diaper manufacturing line because it is so innovative.

Prof. Berger also described her visit to a fourth-generation metal-working business in Ohio. The company got its start making industrial boilers. During the Iraq war, the company realized that it could make steel armor plating for Humvee cars. The company actually had higher-performance steel than the traditional kinds used by the US military. After the Iraq war, when demand for armor dropped, the company saw that it could extend the use of its new steel to aircraft, making the aircraft stronger yet lighter and thus more energy-efficient. The company has gone on to do for the military what it did for business, showing the military how to use a new kind of steel combined with a new kind of welding to develop strong but more energy-efficient solutions. This type of innovation makes a fundamental contribution to the economy, enabling economic growth and the creation of new jobs while reducing costs and promoting more energy efficiency.

1.2. Innovation Inputs

Drawing on the metal-working company example, Prof. Berger asked what kinds of inputs were needed to get that kind of innovation and result. Prof. Berger's diverse research team of 21 faculty and researchers (the PIE team) examined six different kinds of innovation inputs: worker skills, capital, suppliers, learning, facilities, and policies.

The researchers conducted 265 interviews across multiple countries, mostly in the US but also in Germany, China, and other countries. They asked companies how they develop a new innovation and where they get the people, the capital, the suppliers, the knowledge and the facilities to commercialize it. The interviews were meant to reveal, for example, whether Apple's outsourcing model applies to emerging industries like biotech, new materials, and medical devices. Can these new industries be organized in the same way, with a separation of the activities of R&D and design from other functions? Can the venture capital (VC) finance model that allows Cisco to grow also apply to these other industries?

1.3. Innovation Startups Lack Funding for Production Commercialization

In addition to conducting company interviews, the PIE team also analyzed data on innovation startups, examining the 150 non-software companies that grew out of MIT from 1997-2008. The purpose of the analysis was to determine whether the startups were able to scale up to their innovation to commercialization. Prof. Berger acknowledged that the 150 companies studied were highly privileged (that is, they had emerged from big labs and had access to a good labor). Thus, if these companies could not scale up to commercialization, the less-privileged firms would face even greater struggles.

Prof. Berger found that the 150 companies received VC funding for longer than the typical five years, but even after 10 years, the total amount of funding averaged only $75 million. As a result, of the 15 companies that were closest to commercialization, almost none had been able to scale up to commercialization in the US. The companies had strong ties to VCs, but they couldn't get the $30-50 million they needed to build production facilities in the US, so they went to Asia and Singapore. Companies in the energy sector, in particular, moved to Singapore and Russia where they were able to access higher levels of funding. Some of the companies were purchased by large US companies, but few had IPOs. Thus, companies that started in MIT labs were ending up overseas because of a lack of the level of funding in the US that would have taken them to market here.

This lack of funding for a home-grown scale-up presents two big problems, Prof. Berger said. First, it means that MIT research -- 80% of which is funded by US tax dollars -- is ending up creating jobs overseas. Second, it means that the learning that takes places as products move from the lab to the prototype stage and then on to initial production gets off-shored because the activity is taking place outside the US. The US is losing the learning that takes place in the course of commercialization, Prof. Berger said. As a result, it's much less likely that new stages of innovation will take place in the US. Just as the final stages of production have shifted to outside the US, so too could the county's innovations migrate to other nations.

1.4. Mainstream Manufacturing Companies and the Skills Gap

PIE researchers also analyzed mainstream manufacturing companies in the US. Specifically, the researchers examined fast-growing manufacturing companies with more than 20 employees that had doubled their revenues between 2004 and 2008. This eliminated the very big organizations, leaving the small and mid-sized enterprises (SMEs). The team then surveyed all these manufacturing companies in four states to ask: "how long did it take you to fill your last vacancy?" as an unbiased indicator for any skills gap.

The PIE team sent out 1000 questionnaires. Three-fourths of the establishments said they were able to find the workers they needed in less than one month. A significant minority reported having difficulty, and 5% had vacancies for three months or more. When asked the cause for the hiring delay, 50% of companies cited worker skills rather than worker attitude as the problem. Only 7% cited problems of drugs or work ethic.

Digging deeper into the missing skill sets, the researchers found that the level of skills needed were "frighteningly low"; 60-70% of vacant jobs only needed some combination of basic reading, writing or arithmetic, while only 50% of jobs needed all three. Yet finding people with even these skill sets was proving difficult for some companies. The retirement of baby boomers could exacerbate this problem.

1.5. The Inexorable March to Services

Prominent economists such as Lawrence Summers and Gary Becker say that it's natural that the number of manufacturing jobs in the US would decline, just as the number of agricultural jobs in the US declined after industrialization. At the turn of the century, 40% of the US workforce was employed in agriculture, compared to only 2% now. These economists say that higher productivity leads to fewer workers needed. But, although that is true for food -- Americans can't (or should not) eat more than they do -- that is not true for manufacturing. The US appetite for manufactured goods is enormous, and the US has a huge trade deficit as a result, which is a big problem for the economy.

Economists also say that the inexorable march to a services economy requires fewer manufacturing jobs, but in fact most companies offer a bundle of manufactured goods coupled with services. The services aren't separated from the goods but accompany them. Prof. Berger gave the example of company in Ohio that sells half-sleeves for oil pipes, but along with those sleeves it sends out technicians who help customers install the components on oil platforms. The product and the service are linked, she said.

1.6. Financial Markets Force the Transformation of Corporate Structures

In the 1980s, the US economy was dominated by vertically-integrated companies such as IBM, Texas Instruments and Motorola. These firms did everything from R&D through to manufacturing, distribution, and logistics. They located corporate activities close to lead customers. Now, organizations have been radically transformed by the financial markets. Financial markets demand that companies focus on their core competencies and divest the non-core operations. Wall Street rewards companies that shed manufacturing plants and workforces to hit quarterly profit goals.

As a result, corporate functions are now distributed between the home society and the host society. Few US companies today are vertically integrated; most are pure-play investments. In May 2013, activist firm CalPERS demanded the manufacturing firm Timken separate its tapered bearings division and its specialty steel division into two companies, so the pure-play trend continues.

The pressure from the financial markets to raise stock prices on a quarterly basis drives US companies to divest their manufacturing because they will get higher returns as pure play companies. CalPERS is pushing for higher earnings in order to fund the pensions of retired teachers, and the financial argument wins but may result in a long-term loss in manufacturing know how for the US.

In contrast, when DuPont invented nylon in the 1930s and 40s, the company was willing to invest for 10-15 years in the corporate labs that developed nylon as well as the mass production facilities required to commercialize the innovation. DuPont had relationships with long-term equity partners, and it invested in facilities and the skills of lifetime workers in a way that none of the 150 startups studied can today because of the change in corporate structures.

Moreover, modern companies are too small to fund the kinds of training that large companies previously marshaled. For example, Kodak in its heyday had hundreds of apprenticeships. Today, dozens of small high-tech optics firms exist in Rochester (Kodak's hometown), but none of these companies can support the hundreds of apprenticeships that Kodak offered. PIE researchers are seeing big holes in the US economic system as a result, Prof. Berger said.

In response to a participant's question, Prof. Berger said she does not see the business funding site Kickstarter replacing the funding mechanisms needed to invest in new ideas, because the scale of Kickstarter funding is too small. Funding production requires investments in the $30-50 million range. The US is not short on VC funding, but it is short on the larger-scale funding that is often needed, she said.

1.7. Lessons from Germany

People assume that manufacturing has to disappear in an advanced high-wage economy as jobs move to low-cost countries, but Prof. Berger found that the German example proves that's not true. In Germany, the "mittelstand" companies (SMEs) are doing extraordinary well despite factory worker wages that are 70% higher than those in the US. The US has only 11% work in manufacturing, but Germany has 22% of the workforce employed in manufacturing. Germany has a trade surplus, even in its trade with China. Thus, it's not inevitable for manufacturing to leave a high-wage economy.

When PIE researchers went to Germany and asked the same questions of how companies get a new idea to market, they got very different answers than they got in the US. For example, a German machine tool maker for the auto industry began considering diversification outside the automobile industry. He wondered whether his machine tools could be applied for making artificial knees. So he went to the regional technical institute that did work on medical devices and worked with technical universities to learn from them. Then he went to his local banker and got the funding he needed to expand into the medical device industry.

When a German company is ready to scale a new innovation, it can tap local banks, apprenticeships at technical institutes, and its loyal workforce. Dense industrial ecosystems make jobs and companies sticky, and there is real innovation in these industrial ecosystems. China and Germany have these kinds of industrial ecosystems. These company strategies and options are not available in the US, Prof. Berger said. For one thing, US banks are now national entities that don't have the kinds of local relationships that were part of the industry in the past.

1.8. Home Alone

Prof. Berger authored a book based on the PIE research, and if she'd been able, she would have titled the book Home Alone. US companies trying to scale up innovation have to do it alone, without local banks, without local technical institutes and apprentice programs, and without research consortia. US companies have to go it along, and that's a problem. The US doesn't lack ideas but lacks the public goods of universities and consortia and local banks that would help scale an innovation to commercialization.

An example of an industry research consortium in the US is SEMATECH. In 1987, when the semiconductor industry in the US was almost dead, companies came together with suppliers and universities to work cooperatively and collaboratively through SEMATECH. As a result, the industry now employs 250,000 people and is the strongest exporter in the US. Other industries could learn from this research consortia model, where companies operate together to reduce the risk of bringing innovation to market.

1.9. Conclusion

The most urgent challenge is for the US to rebuild its manufacturing capability, Prof. Berger said. As energy costs come down and labor costs in Asia rise, the US has an opportunity to bring back more manufacturing. The country has an opportunity to rebuild its economy and regain lost capabilities of providing capital for startup activities and a skilled workforce.

2. Big Data Challenges and Opportunities, Prof. Sam Madden, Director, MIT Big Data Initiative

The rise of "Big Data" amused Prof. Sam Madden. Analyzing data to find patterns and insights is not new technology. What has changed is the access to so much more data than was possible in the past, combined with increased computing power that enable companies to collect all the new data. Companies naturally wonder how to get value from all this data. Prof. Madden outlined the challenges of big data, the opportunities, and described three of MIT's tools in the Big Data Initiative.

2.1. Challenge: Volume, Velocity and Variety

The problems of big data are often called the 3V's -- volume, velocity and variety. First, the amount of data -- the sheer volume -- is huge. Many companies and organizations have huge data stores. Not only are the accumulated volumes high, but so are the velocities of data. Data is being collected faster than ever before from many sources, such as sensors and cell phones. But these problems actually aren't new, Prof. Madden said. Companies have been processing more and more data for some time, and petabytes of data can now be analyzed -- provided that the data is in the same format.

Variety, the third "V," is the challenge. It's not just a matter of more data, but more sources and kinds of data derived from a more extensive range of sources.. The result is incompatible data formats, non-overlapping segments of data, and inconsistent values for data on the same issue. Deciding which data points are right, what they mean, and how they can be combined often requires a labor-intensive process which cannot be scaled up quickly.

Finally, many of the three V problems are scalability problems in which the required computer resources are not linear in the volume, velocity, or variety of data. Having 10 times as much data might make the problem 100 times, 1000 times, or even a billion times harder for the computer. This exponential rise in complexity is a real challenge that creates problems such as how to pick the best subset of data or data sources for a given big data challenge.

2.2. Example: What Drives the Cost of Treating Lung Cancer?

Prof. Madden described an example of a Big Data problem, namely analyzing a set of mixed data to identify what contributes the most to the cost of treating lung cancer patients. To analyze this, researcher James Michaelson tapped numerous sources, including the world's largest cancer patient database of 173,000 patients, cross-linked with the death registry, a tumor database, hospital billing records, lab test reports, imagery such as MRI scans, and genome data. Dr. Michaelson looked at all of these databases and found that the median cost of treating a lung cancer patient was $12,000, but the most expensive 10% of patients cost $69,000, which is a 5X difference. What was different about the highest-cost patients, Dr. Michaelson wondered? Was it the length of care, the stage of cancer, or possibly the age of patients and whether or not they had insurance?

These intuitive variables failed to explain the variation, however. As it turned out, the primary difference driving the cost was which doctor the patient saw. Some doctors at the hospital incurred relatively high costs by ordering tests and designing more aggressive treatments, yet the health outcomes for all patients were the same. Lung cancer patients tend not to survive, regardless of how extensive their care is, but the extent of care can drive up costs. Arriving at this insight from Big Data, however, was very labor intensive, requiring running regression after regression to find this one fact. That human-intensive step will limit the opportunities to be gained from Big Data unless computer science tools can be built that will allow people to get insights faster, explained Prof. Madden.

2.3. Example: Predicting Flight Delays

Prof. Madden's second example -- predicting delays of airline flights -- illustrated the second Big Data problem: that of inconsistent data sets. Commonly-used systems such as FlightView, FlightTracker and Orbitz contain data on all scheduled airline flights, listing their departure and arrival times. But surprisingly, the published departure and arrival time for the identical flight varies across the sources. Even the scheduled flying times varied substantially. The reasons behind these variations are not clear – one possibility is confusion over estimated versus actual times in the databases – but the result is the same: inconsistent data. Such inconsistency across data sets is very common, Prof. Madden said, which makes it harder to analyze and correct the data. Again, tools need to be built to address these inconsistencies so that the data can be analyzed more quickly and effectively.

2.4. Monomi: Private Big Data with an Encrypted Database

One formidable challenge of Big Data is how to protect the privacy of data without restricting the analytical potential of the facts and figures. For example, keeping health data private is important, but at the same time analyzing data on medical conditions, treatments, and outcomes could improve the quality of healthcare for all. How can data such as the lung cancer data be analyzed without putting patients' privacy at risk?

The typical way to afford protection is to encrypt data so that the details cannot be recognized or understood without the encryption key. Unfortunately, encrypted data is harder to analyze. In particular, fully randomized encryption, which is the safest form, randomly assigns values to numbers even when those numbers have the same value. For example, the number "100" in a list would have different encrypted values each time it appeared, even though each instance of 100 has the same value. With randomized encryption, it's not possible to see how many times "100" appeared.

To avoid this problem while still protecting privacy, a technique called "deterministic encryption" could be used. Deterministic encryption allows all the instances of the same value to look the same. Alternatively, "order-preserving encryption" is another security option, where the order of the values could be sorted from highest to lowest, without knowing their exact values. With order-preserving encryption, queries such as "greater than" could be run, allowing data to be analyzed while still providing protection against system compromises. Monomi is a database designed on these principles of using various types of encryption to obscure the data while still enabling useful queries.. Even if a malicious person obtains the entire database, all the individual records and fields in the database are secure.

2.5. Scorpion: Predicate-Free Analysis

Prof. Madden explained that traditional data analysis uses a predicate-based analysis. With predicate-based analysis, a researcher creates a hypothesis (the predicate) and then analyzes the data to test the hypothesis. That's what Dr. Michaelson did to analyze the variation in lung cancer treatment costs -- create a number of possible predicates or hypotheses and analyze each one. This is a human-intensive step and also can inadvertently restrict the analysis to exploring preconceived ideas about what's happening in the data.

On the other hand, predicate-free analysis does not require pre-conceived hypotheses. Rather, predicate-free analysis tools let researchers discover patterns or gain insights without having to guess what they will find. This technique is also known as "data-driven discovery." The growing variety of data makes data-driven discovery more needed, so that data can be analyzed without human intervention and can explore multi-facetted data sources in unexpected ways.

Scorpion is a tool that answers the question: "why does my data look the way it does?" In particular, Scorpion uses predicate-free techniques to explain outliers (e.g., those 10% of lung cancer patients who cost 5X the median). This is a difficult problem to solve because identifying outliers requires an exponential search across subsets of records and attributes. The scientist or the computer must check all the myriad combinations of subsets of all the records in order to find the outlier effect. Simply searching through every subset would take too long, so the MIT researchers looked for a more targeted searching process to create Scorpion. Scorpion tackles this problem by positing that outliers will be near each other in data space and that the ways in which they a near each other can help isolate the most relevant subsets more quickly. Thus, Scorpion finds the record that most contributes to the outlier value and then finds records near it.

2.6. MapD and the Use of Fast Computers to Analyze and See Big Data

People can often make better sense of data when it is depicted visually and if they can interact with it. Visualization and interactivity with Big Data require extremely high computing power, however. The Big Data Initiative is exploring ways to exploit modern-day hardware to allow fast, on-the-fly computing. As one example, Prof. Madden described MapD, which takes advantage of the extremely high computing power of GPUs (graphics processing units) to visualize massive amounts of data.

MapD can take massive geocoded data sets such as 100 million tweets from Twitter. Each tweet contains a geo-tagged text string of no more than 140 characters. MapD can load all 100 million tweets into the memory of the GPU so that they can be processed in parallel. It is a brute-force technique that scans each tweet, but the parallel processing means that ad hoc analysis can deliver results within milliseconds. In contrast, a normal GIS (Geographic Information System) would grind to a halt trying to run queries on 100 million data points.

MapD can create visual snapshots and animations of word occurrences superimposed on a map. For example, a researcher can ask see every instance of the word "morning" in any tweet shown on a map of the world. The visualization shows a time-based sweep across the world as each region of the world wakes up and someone tweets "good morning" or some other reference to morning. Similarly, a researcher can see rainstorms by mapping tweets that mention "rain."

The occurrence of any word can be tracked in space and time, enabling heat maps of flu outbreaks, for example. Companies can use this technique for brand analysis, such as identifying whether their most vocal customers are located in greater frequency in certain parts of the world, nation, or city. For example, "Starbucks" is a brand with nationwide exposure but has a higher predominance in the West whereas "Dunkin" (as in Dunkin Donuts) clusters more in the Northeast.

Technological and business advances bring increased computing power to data scientists. Next-generation hardware, general-purpose GPUs, and many-core CPUs enable faster processing. Flash memory enables faster retrieval of data; GPUs and "manycore" mean that rather than just running multicore of four to eight processors, now hundreds of processes can be run to replace or augment the CPU, resulting in much greater computing power.

Enrollment in computer science courses is at an all-time high, Prof. Madden said, because computer science is driving so many industries forward. Now is the best possible time to be working on data processing software because of the tremendous excitement around new tools.

What's more, this increased computing power is now more available to individuals and small businesses; not just to large organizations with millions of dollars to spend on computers. In the past, using hundreds of fast computers to process large amounts of data in parallel meant buying hundreds of fast computers, which cost millions of dollars and took month to design, buy, and implement. Now, a single individual or small business can go to a service such as Amazon Web Services and rent a hundred machines for a day or two to run an analysis.

The inventor of MapD is close to commercializing the tool, Prof. Madden said in response to a question from the audience about how far away the tools are from corporate use. MapD's inventor is actively looking for customers.

2.7. Big Data and AI

Asked about Big Data's relationship to artificial intelligence, Prof. Madden noted that artificial intelligence and machine learning are like statistics on steroids, which creates a clear intersection with the kinds of statistics and analytics done in Big Data. As such, programs such as Scorpion are types of machine learning systems that arrive at approximate answers faster. Overall, work on Big Data is creating a lot on additional AI firepower in the form of new software and new analytics.

"Deep Learning" refers to taking data through neural networks to get much better answers, such as facial recognition. By running all the photos of faces on Facebook that have been identified, unlabeled faces can be identified with 98.7% accuracy - which is as good as human recognition. Machines can learn this because of massive data sets that can be fed into the system to deliver breakthrough results. Natural language processing still lags behind what humans can do, but it is getting better due to access to massive data sets. Finally, sensing has revolutionized robotics through super-high throughput sensors on robots that can make a robot much more aware of what is around it.

3. Is Cyber Security the Next Risk Frontier? Dr. Abel Sanchez, Executive Director and Chief Technology Architect, MIT Geospatial Data Center

Hacking into computer systems, a practice that started out as pranks by a few hotshot computer jockeys, has now become a global black market industry. Dr. Sanchez showed a list of the prices for different kinds of cyber attacks. For example, a DNS attack can be purchased for $100 for a day. Hacking into a Twitter account or Facebook account costs $130. Hacking into a Gmail account costs $162. Hacking is now an industry that is growing because of the global market and because it takes only a few years to become proficient at selling these illicit services.

3.1. Cyber Threats: Vulnerable Passwords

Passwords are a big area of vulnerability, Dr. Sanchez said. Passwords are limited to 95 choices for each character, (given 26 letters of the alphabet, which can be upper or lower case, as well as numbers and special characters.) An 8-character password could therefore be any one of 6.6 quadrillion choices. Brute-force attempts to test each option would take 19 days of computing. But, most people do not create truly random passwords, and they follow predictable patterns such as using common words and names, limited amounts of capitalized letters, and the addition of a few numbers, Dr. Sanchez said. By following these few heuristics of starting with an uppercase letter followed by several lower-case letters and then some numbers and possibly special characters at the end, the universe of likely passwords shrinks greatly and can be searched in 2 minutes.

Hackers can also test passwords against an online dictionary. A frightening number of people use extremely simple passwords such as "12345678" or "password." On a random set of 7000 passwords, Dr. Sanchez found that he could decrypt 2000 of them in less than a second simply by using the dictionary. Worse, when passwords are stolen and deciphered, the results are typically uploaded to a commons area for all to see, enabling further patterns to be identified. For example, in the US people often substitute the dollar sign for the letter "s." When 6.5 million passwords were stolen from LinkedIn, 10% were deciphered in thirty seconds, 30% in two hours, 64% in one day, and 90% were deciphered in six days.

3.2. The Growing Surface Area of Threats

The cyber security threat will only continue to grow as more and more devices connect to the Internet. Currently, cell phones outnumber people. And by 2020, there may be a total of 50 billion devices connected to the Internet. When Dr. Sanchez looked around his own house, he found 25 Internet-connected devices including laptops, phones, printers, Kindle readers, a media server, TV, game station, tablets, cameras, and clocks. Any of these devices can create vulnerability. Even electronic cigarettes now can integrate to music players, and all of these vulnerabilities can be exploited. Not only does the flood of new connected devices represent a security threat, but most customers are not demanding better security from device makers. Why should a baby monitor manufacturer spend extra money adding security protection to the device when customers are not asking for it?

For organizations, the surface area of the threat is even larger. MIT runs an open network comprising some 100,000 connected nodes. Of these, only 30,000 are known nodes, meaning that the remaining 70,000 are unauthorized. MIT was in fact the subject of an activist attack which resulted in MIT going dark, and control of the MIT servers was transferred to North Korea.

Another problem is the long lag time from when vulnerability is identified to when a patch is created and implemented. On average, the time between detection and patch takes six months, and some machines never get patched, especially at universities or labs. Another lag time is how long it takes for the vulnerability to even be detected. The average detection time is two years. Nieman Marcus was comprised for six months before the actual attack was launched, as the perpetrators strategized the most effective way to steal the credit card data they wanted.

3.3. The Fortress Model No Longer Works

In the past, companies thought they could put up a firewall and keep malware out. But now, employees often take devices such as laptops and smart phones out of the office where they may be compromised, then bring them back inside the firewall. The majority (80%) of android phones have malware, Dr. Sanchez said, which presents problems when the devices are brought into workplaces, which they routinely are as "bring your own device" policies are becoming more common. Finally, at most organizations, 80% of users run unauthorized apps, because control of devices and applications is no longer centralized. A major government organization was shut down for a week after an employee went out for lunch, surfed the net using a personal laptop, and then returned to the office with the machine. A virus in the laptop subsequently compromised the agency.

Mobile technology and cloud storage can run afoul of privacy regulations. For example, a doctor purchased a new laptop and brought it into his hospital. The laptop started syncing his emails, which created a violation of patient privacy laws (HIPAA) and required a team of 60 people to go through every single email that was synced to see if there was a breach of HIPAA law. The doctor was fined for each breach. The same thing could easily happen again, however, because hospital policy still allows doctors to use their own laptops at the hospital and in their private practices.

Most organizations don't have budgets for cyber security. The above-mentioned hospital had a total of four people handling cyber security. After the HIPPA incident, Deloitte was brought in to do an audit, and Deloitte determined that the hospital should have a staff of 40 people on cyber security. The hospital hired 16 new employees, which was still only half of the total staff recommended for an organization its size.

3.4. The New Virtual Machine

More and more computing is being done from the browser, such as launching a PDF reader from the browser. These changes improve productivity and performance, so they are being implemented widely. It's also too expensive to write different applications across all systems, so computing is being pushed to apps to reduce costs. As a result, the majority of vulnerabilities are now with browsers: zero-day, plugins, PDF, JAVA.

3.5. Standards and Best Practices

The leading standard that addresses cyber-security is called NIST 800-53. The standard is very thorough but perhaps too big, Dr. Sanchez said. Revision 4 is the most recent version of the standard and contains well-documented controls. Dr. Sanchez suggested that organizations seeking to improve their cyber security start by looking at these controls, doing risk assessments and prioritizing among them to address their highest-priority areas.

Dr. Sanchez recommended two other sources, in addition to 800-53, for organizations to visit to improve cyber security. First, the Top 20 Critical Security Controls, originally from the NSA, is available at http://www.sans.org/critical-security-controls and it provides specific instructions on how to address the vulnerabilities. The second recommended source is from Mitre Corp, at http://cve.mitre.org/about/index.html which addresses common vulnerabilities. Companies can subscribe to this service and receive patches.

Companies need not spend a fortune on these measures, Dr. Sanchez said. Good open source stacks are available from Backtrack, Nmap, Snort and Netwitness, among others.

3.6. Four Research Projects at the MIT Geospatial Data Center

Next, Dr. Sanchez described a set of four research projects going on at his lab.

Simulator

Dr. Sanchez's Simulator simulates an organization's network from the ground up, so that the organization can see the impact of apps on a global scale and can see what needs to be addressed to tighten cyber security. The Simulator shows a typical event cascade: what CPU is used, what servers are impacted, and so forth. The agent model of the data center can be comprehensive, with all the apps and users, but once it is developed, the organization can test all kinds of what-if scenarios.

Malicious Activity Detection Systems

Malicious Activity Detection Systems (MADS) are a potential improvement upon malware detection systems. Current malware detectors compare potential suspicious code against a blacklist database of signatures. But today's rampant proliferation of viruses, various tricks by virus makers, and zero-day vulnerabilities, cause the signature-matching approach to miss between 50% to 90% of viruses. In contrast, MADS works by looking at anomalies in the network traffic and behavior. Although the methods of hackers might adapt rapidly, MADS works because the goals are somewhat more constant (steal sensitive data, disrupt critical systems, embezzle funds, hide rogue trading, etc.), which constrains the pattern of activity to something more detectable than are the hyper-variable bits of malware code.

Intrusion Avoidance and Fraud Detection

Organizations such as the Department of Defense are exploring more secure authentication methods than just passwords to prevent unauthorized access. Unlike passwords, which offer only a single point of protection or detection, organizations can use geospatial data and human behavior patterns over time to detect anomalous behavior that could indicate an insider threat. For example, employee ID cards or cell phones can track a person's spatial movement throughout the day. Most people follow the same patterns day after day. If suddenly a person is using a printer at 5am or is using a printer four departments away from where they usually print, that anomaly can be investigated to determine if it is a threat.

Visualization

Many people point to cyber security being a difficult area to manage because it is not visible. The abstractness of potential vulnerabilities makes security especially problematic. So, Dr. Sanchez set up a little test to monitor everything that happened on a brand new laptop plugged into the MIT system. Thousands of attacks flooded in. Dr. Sanchez analyzed the origins of every attack to show the cyber security threat at MIT. He then showed a visualization of the data generated. Specifically, that laptop -- which was simply plugged into the system but never used by anyone -- received an attack from every country on earth and was attacked every second of the day. MIT has had an open network policy throughout its history, with no consideration to change it. But now, after the administration saw this visualization, MIT is considering the option of putting up a firewall. The firewall will not be mandatory, but it will be an option. The visualization showed the originating locations of all the attacks on this one laptop on the MIT network. The swiftness, vastness and persistence of the attacks gave the administration pause.

3.7. Conclusion: Big Challenges but Simple Solutions Do Work

The challenges of cyber security research are threefold: there isn't enough data, it takes a long time to get data, and once the data is received it takes a long time to clean the data so that it can be worked with. On the positive side, however, the solutions of what works with cyber security are surprisingly simple. Dr. Sanchez described three techniques: peer groups, multiple data sets and data integration.

Study Peer Groups

First, data from peer groups can be analyzed to detect anomalous behavior. For example, to detect overcharging among medical professionals, peer group data can be analyzed. Looking at groups of cardiologists, for example, can give typical baselines of charged amounts. A cardiologist who charges ten times the norm can be a red flag for possible fraud. Similarly, looking at the patterns of tax collectors and where they audit revealed that one tax collector was auditing everyone in one particular town -- because the auditor had a bias based on the ethnic origin of inhabitants of that town. Thus, peer group analysis can show anomalies and spikes that warrant investigation.

Get Additional Data

The second technique is to look at more than one data set. Adding in external information, such as weather details, can reveal additional patterns that weren't possible to see before. However, using multiple data sets takes time and requires more planning..

Integrate Data

Finally, data integration is a third technique: using multiple inputs and triangulating across the data. That is the technique Dr. Sanchez is using with the DoD, to detect insider threats by noticing that an employee had gone four departments over to print something or that the cadence of their typing is not following their normal cadence, indicating that an intruder could be using that computer. But data integration is hard because many organizations have fragmented data systems.

4. The New Robot Age, Prof. Julie Shah, Head of the Interactive Robotics Group, MIT Computer Science and Artificial Intelligence Lab

Prof. Julie Shah envisions a production floor where humans work collaboratively with robots. She uses her training in planning, decision-making, and control software to design algorithms that would make industrial robots safe and intelligent enough to work alongside humans.

4.1. The Extent of the Opportunity

People assume that 80% of automotive assembly is done by robots, but the true number is only 50%. In fact, most of the final assembly is still done by humans and takes up 50% of the manufacturing space. In the airplane manufacturing industry, 80% of assembly is done by humans, and in cell phone manufacturing, 90% of the work is done by humans. The automated work in the aerospace industry is done by "monument" automation systems -- huge robotic towers for drilling and assembly.

The two main reasons for the limited use of robots are 1) safety and 2) lack of a way to quickly reprogram robotic systems to handle a change or disturbance to their planned tasks.

4.2. Current Limits on Robot Use

Robots could be more pervasive on the factory floor if the safety of their human coworkers could be better guaranteed. Industrial robots are so large and powerful that they can be potentially harmful to humans if the two operate in the same space. For that reason, industrial robots are sequestered inside cages where they do their part of the work. This means, however, that even when a piece of work could be off-loaded to a robot, the reassignment would require a physical move of the task to inside the robot cage, which may or may not have sufficient space to accommodate it. Even when robots work inside cages, their work ceases if a human has to enter the caged area for any reason. If such entry happens often, the productive value of the robots is lost due to the idle time. Therefore, companies often simply let the task continue to be carried out by human workers.

4.3. "Inherently Safe" Robots

Prof. Shah described a new type of hardware for industrial robotics: "inherently safe robots" or "mostly not dangerous" robots that won't seriously injure a human if they accidentally hit them. The new robots are instrumented with sensors to be more aware of their environments and avoid hitting people or other objects. New safety specifications are emerging for putting robots on a mobile platform that will let them navigate the factory floor safety through sensing. The robots will slow and stop when a person approaches. This improves safety and gets robots out of cages, but again if robots are simply programmed to just to stay out of people's way, robotic work will cease whenever a person is near, and productivity will suffer.

One way to tackle this productivity problem is to enable robots to quickly re-start work with a new schedule of tasks after having stopped due to a human or other disturbance. This dynamic scheduling, however, is a computationally difficult problem because of the sequencing of tasks and constraints on resources that must be taken into account. Current AI programs require 30 minutes to calculate a new sequence of robotic actions. If the robot work is stopped due to the presence of a human, it takes another 30 minutes to reprogram the robot.

4.4. Analogy: Processor Scheduling

The scheduling problem is difficult because the temporal and spatial constraints are highly intercoupled. An example of a temporal constraint is that of having to wait for paint to dry before the next task can be performed in the designated area. A spatial constraint is that a human and robot (or two robots) can't occupy the same physical space at the same time. Where the robot goes is restricted by the choice of location and the movement of other machines and humans.

Prof. Shah was able to tackle these difficult problems by using the analogy of how computer processor scheduling in a multicore computer works. By analogy, agents (robots and humans) are processors that share a physical space the way that processors share memory space. Tasks are assigned in sequence such that they access the shared resource in mutual exclusion.

To simplify the scheduling problem -- which even for one processor would be an exponentially hard task set -- Prof. Shah assumes the lower-bound wait constraints are pure idle time. Then, for the remaining lower-bound wait constraints, she uses a "Russian doll" method: a worst-case nesting of the lower to the upper to get a conservative scheduling estimate. Using this approach, Prof. Shah can schedule 10,000 tasks in less than one second (compared to the fastest AI solvers which time out after 30 minutes trying to compute just 100 tasks). Thus, Prof. Shah's approach is a huge win. In terms of quality, the resulting schedules are within 10% of true optimal.

Taking this approach to the multi-agent setting, Prof. Shah uses a fast schedule feasibility test to see if a task path is possible. Once the path is found, the path is committed to. Committing to the path reduces uncertainty and enables a less conservative decision to be made in the future. Prof. Shah then embeds the process in a simulation loop and does task allocation and sequencing until a schedule is found that meets all the objectives. For a multi-robot system, this approach can generate a schedule for 700 tasks and 10 agents in 10 seconds or less, compared to AI solvers that time out after 30 minutes computing 50 tasks for 5 agents. As before, the quality of the solution is within 10% of optimal. Compared to current proprietary systems, the schedules are also 10-20% shorter, enabling greater productivity. Overall, these fast processing times enable schedules to be recomputed anytime a person has to enter the factory floor with a robot.

4.5. Training Robots

Prof. Shah, who worked at Boeing before joining the MIT faculty, knows from experience that another factor must be taken into account when manual work is involved: the tasks are not done exactly the same way each time. That is, humans aren't robots. They work slightly differently from day to day and shift to shift. If humans and robots are to work alongside each other safely, they have to be able to predict and trust each other's behavior. If a person thinks the robot is unpredictable, the person slows or stops their work. Similarly, robots are programmed to simply stop work when they sense a potential collision with a person. Integrating the work of humans and robots requires a better approach.

To date, factories have created statistical models of human behavior and translated the outputs to robot tasks. Another factor is that training of robots is one-way; that is, teaching robots by rewarding "good" behavior and punishing "bad" behavior. But research shows this type of training method is one of the worst ways to train. Instead, looking at how human teams are trained reveals that cross-training achieves better results. That is, each team member learns his or her own task and then learns the tasks of each of the other team members. People switch roles. This teaches them not only their own jobs but lets them better understand and anticipate how their team members will act when performing the other jobs of the team. People are good at incorporating this type of learning into their own behavior. Prof. Shah hypothesized that robots could be trained via cross-training, too.

To test the hypothesis, Prof. Shah randomly assigned 36 test subjects to either cross-training or reward training with a simulated robot. The subjects worked with a point-and-click robot (not a real robot, so there were no issues of safety). After the training, she had them work with a real robot and measured the robot's uncertainty and latency as well as the subjects' responses to a questionnaire about their experience. In the cases of reward-based training, robots were much more hesitant and unsure of how humans would behave compared to the cross-training method. Measuring the same task (with the human placing 3 screws in 3 holes while the robot used a screw driver on those same screws) after cross training, the robots' pace increased 70%. The robots had a better model of human behavior after cross-training than with traditional reward training. The human-subject questionnaires also supported that people felt more comfortable working with the robots after cross-training rather than reward training. They trusted the robot more and felt that the robot performed as they expected more often. The person understood better what the robot would do.

4.6. Results and Benefits

Overall, Prof. Shah's results show that factories don't have to trade safety for efficiency when mixing people and robots. This experiment let Prof. Shah implement a human-aware planning model that resulted in a 6% faster task execution and a 1.45% larger mean separation distance between robot and human after using cross training. Making robots adaptive can increase the efficiency of the task as well as the physical distance between human and robot.

Many factory tasks are still better done by humans, such as object recognition, work that requires dexterity and artistry. Nonetheless, robots can shoulder the heavy lifting and delivery of materials to enable humans to pick the components they need and manipulate them. The model is akin to humans being surgeons and robots being their operating room assistants.

Prof. Shah is applying her algorithms at a BMW plant, in which mobile robotic assistants would bring workers the tools they will need to do their jobs. This approach will improve the efficiency of the manual work. The goal is to make the robots smart enough to be safe but to improve the overall efficiency of the work to be done. Employing Prof. Shah's algorithms means that robots no longer need to be confined to cages but can work alongside humans.

4.7. Implications for Manufacturing and Supply Chain

One of the promising applications of this kind of fast scheduling is to enable more customization of products. If robot work can be re-programmed quickly, the manufacturing line can be more responsive to the needs of customers and can be rebalanced based on what customers want. Similarly, the fast rescheduling enables companies to respond better to disruptions or disturbances, such as a late arrival of parts. Work could possibly re-sequenced on the fly so that deadlines are still met.

4.8. Future Research

One of the new lines of research which Prof. Shah is pursuing is that of taking video motion capture movies of people doing work and then translating that to a robot's task plan, to show a robot how to do the task using its own motion planner. This approach to training could be another game-changer because it would enable robots to be trained (programmed) by people who don't need to know arcane robot programming languages. Instead, the person would show the robot how to do the task and the training could be accomplished much faster.

5. 4-D Printing and the Self-Assembly Revolution, Skylar Tibbits, Director, MIT Self-Assembly Lab

Computer science -- computation and coding -- is changing the way objects can be designed and built. The increasing availability of 3-D printing, especially multi-material 3-D printing, is opening up new possibilities in the shaping and functionality of manufactured components.

5.1. Self-Assembly

At the molecular and nanoscale levels, molecules naturally self-assemble themselves based on the laws of physics and the effects of energies in the environment. At the macro level of our daily world, however, objects only assemble through the carefully guided application of artificial forces, such as workers with hammers building a product. But what if macroscopic objects could assemble themselves? That vision is possible with programmable materials -- materials into which instructions are printed via 3-D printers. With these instructions, smaller parts come together into larger parts through instructions on how to interact with their neighbors. The assembly instructions are built into the parts rather than carried out by an external assembler such as a factory worker or robot.

Although it sounds futuristic, Skylar Tibbits is already printing these objects in the MIT Self-Assembly Lab (SAL). He showed an example of a jumble of black and yellow objects in a flask. When the flask is shaken (that is, when natural non-guided energy is applied) all the yellow objects self-assemble into a yellow ball, and all the black materials self-assemble into a separate black ball. The person (or any actor) doing the shaking needs no knowledge or training on how to assemble the objects -- the objects assemble themselves through random shaking.

Self-assembly refers to disordered parts assembling themselves through non-guided means into more ordered forms through interactions with each other. Self-assembly does not force items into shape through brute force. Rather, noisy energy gets materials excited, and they assemble themselves because the design of the part is such that it naturally interlocks with other parts as the parts are jostled about. This is the way biology works, Mr. Tibbits said. There aren't any molecular hammers inside of cells; self-assembly takes place through interaction.

The MIT Self-Assembly Lab focuses on materials, geometry and the interaction between parts. By carefully selecting the geometry, certain parts fit together with each other better than with other parts. Parts find each other through passive energy (such as agitation, sunlight, pressure or heat). Error-correction occurs using weak local interaction and redundant systems. For example, in the case of black and yellow parts in the flask, sometimes black and yellow parts mistakenly combine but they don't lock together as tightly as correct black-with-black or yellow-with-yellow part combinations, so the erroneous combinations tend to fall apart. Thus, successful structures hold together and errors are weeded out, guaranteeing precision of the part.

5.2. Size Matters

Using 3-D printers and programmable materials to build objects has limits, however, due to the bed size of the printers. Low-cost printers tend to be small. Mr. Tibbits joked that printing a skyscraper would require a skyscraper-sized printer unless smarter solutions are found.

The smarter solution is to print smaller parts that can assemble themselves into larger structures. SAL is also working on compressing materials into smaller scales and then "unfolding" them. By embedding instructions into the materials, it's possible to print small, dense structures that can then unfold. In Mr. Tibbits' demonstration, he created a 50-foot long unfolded chain out of a small folded set of links only five inches in length by unfolding it. Similarly, the embedded instructions in programmable materials can tell the structure to change shape, such as to form a chandelier shape out of a chain. The process is akin to the folding telescopes sent out into space. Compactly-configured materials can unfold or reconfigure themselves into larger shapes.

5.3. 4-D Printing: Objects Change Shape Over Time

4-D printing refers to using 3-D printing technology but adding the element of time. In traditional 3-D printing, the printed object is static. It comes out as a chess piece, for example, and stays a chess piece. But 4-D printing refers to embedding instructions into the materials such that they would change shape at a later time. For example, an object can be printed as a tube; then when the object detects a new condition, such as moisture, it follows its preprogrammed instructions to fold itself into a cube. A real-world example could be an automobile tire that changes its tread pattern in the presence of rain or snow.

4-D printing works by printing smart materials that have designed-in actuators and sensors that tell them how to fold. The key to creating 4-D objects is to use multi-material 3-D printing and use ingredient materials to respond to the environment. Many of Mr. Tibbits' demonstrations combined a rigid plastic that creates structure, mixed with a moisture-sensitive polymer that acts like a sensor and actuator. The printed object might look like a straight tube or flat sheet when first printed. But when exposed to water, the moisture-sensitive polymer expands significantly to act like a muscle that actuates various hinges and folds made of the rigid material.

4-D materials could change in complex ways over time if the printing is done by depositing even greater varieties of materials: some layers would be activated at a later time. Complex shapes (or changing shapes) could be achieved via hierarchical assembly -- the primary structure would form first and then a secondary one would form later. Early structures are formed using magnetism, materials' properties, adhesion, hydrophobic or hydrophilic tendencies, buoyancy and geometric locking. There are many different ways to get materials to interact in smart ways, Mr. Tibbits said. Precise parts can self-assemble into increasingly more complex parts.

5.4. Revolutionizing Manufacturing

Currently, manufacturing processes use robotics and brute force to shape and assemble materials, but Mr. Tibbits' research into self-assembly could obviate the need for the skilled assembly of parts. Instead, parts would assemble themselves through their geometric shapes and instructions for interacting with each other.

This new paradigm for self-assembled manufacturing would use abundant materials and existing energy to guide materials to self-assemble. Minimal structures can be printed quickly and cheaply and then could assemble themselves into increasingly more complex structures through the application of energy. The energy sources needed are renewable and already exist: sunlight, gravity-fed systems, wind and water, for example. Specialized one-off machine tools would not be required because the parts would self-assemble into the needed shape.

New manufacturing infrastructure would not be needed. This is a materials solution: programmed materials responding to the materials around them to form into parts. Lamination, knitting, weaving and extrusion could all be done. The only change is that the materials used are programmable and can communicate with each other and respond to the environment. These materials are no more expensive than current materials, because current abundant materials can be used, such as wood. The addition of the instructions would mean that, for example, the piece of wood would take a different shape based on the direction of the grain. By putting code into the materials, "Dumb materials can do smart things without more money," Mr. Tibbits said.

5.5. Overcoming the Limits of Current 3-D Technology

Today's 3-D printers are limited in their uses for manufacturing due to their small bed size, the length of time it takes to print a single object, and current software tools. But, solutions to these problems already exist. The problem of size is addressed through printing of dense structures that unfold and reassemble themselves into larger structures. Although injection molding is much faster than 3-D printing at making the component parts, injection-molded parts then require time-consuming and labor-intensive assembly. In contrast, 3-D printed parts could self-assemble, making human assembly unnecessary. Indeed, 3-D printing may save time compared to traditional manufacturing because self-assembled parts don't need assembly time and human labor, thereby reducing total production time.

5.6. Revolutionizing the Supply Chain

These developments could have a major impact on supply chains. For example, objects might be shipped in flat, 2D form, that can stack much more efficiently for better asset utilization. The objects then take their final 3-D shape via self-assembly or folding at the customer site. Printing can be done cheaply and the final assembly is self-assembly that can take place in any location, with no human or mechanical labor needed. In addition, packaging could change over time according to the ambient conditions, making new packaging solutions possible.

4-D printing, in which objects can change over time, has the largest revolutionary potential. Imagine purchasing a pair of sandals that can reshape themselves into close-toed shoes when it starts to rain or that become dress shoes when walking on carpet. Sportswear companies are already working with Mr. Tibbits on linear stretching and folding that can be done without forming the structure.

Consumers would need to buy fewer physical objects if the objects could reshape themselves in response to the environment. Similarly, supply chains would shift if products could self-repair or if they could disassemble for recycling.

Mr. Tibbits -- an architect by training -- originally thought he would be working with the construction industry on construction materials, but companies from many different industries have approached him, including sportswear companies, infrastructure firms like water and electric utilities, the space industry, medical products and defense industries. The principles Mr. Tibbits studies, self-assembly, replication, programmable materials ,all use the same principles and energies and thus can apply to any industry that needs physical objects.

6. Transforming Education through Online Learning, Prof. Sanjay Sarma, Director, Digital Learning, MIT

Classroom-based education started almost 1000 years ago in Bologna in 1088. A painting of a lecture hall from 1308 with a lecturer, rows of students, books, sleeping students, and whispering students shows that classrooms have not changed much in all those centuries.

6.1. Disruptive Trends

In order to survive, however, the education industry must think about the same trends that are disrupting other industries, namely globalization, unbundling, mobility, the emergence of new consumers, and the growth of cloud computing. Just as these changes are transforming other industries, they could also transform education.. Consider the trend of unbundling: at MIT and most universities, you have to buy a whole degree program. Why can't students buy a course for 99 cents the way they can buy songs? Perhaps students should be able to choose their own customized course playlist.

Moreover, today's students are a new breed: they are focused on real-world problems, have a global outlook, tend to be entrepreneurial, socially aware, mobile, and wired. Many of begin their studies at MIT already knowing how to program. They've probably developed their own websites or established themselves as amateur journalists with 100,000 followers on their blogs. And they have seen their parents laid off from jobs, an experience that has made them skeptical about corporate loyalty. These young people arrive at college with different expectations for work. They are much more product-focused than previous generations, and interested in the context, not the cubicle, Prof. Sarma said.

6.2. Disrupting Education: edX

Academia has faced only the occasional disruption, such as the printing press and blackboard, and the profession has not yet been disrupted by the Internet. Disruption will come, however, so MIT launched a new venture, edX, designed to reinvent higher education. MIT and Harvard each contributed $30 million to edX in June 2012 to bring online learning to the world, providing free education on an open source platform. New York Times columnist Tom Friedman called 2012 "the year of the MOOC" (massively open online course).

Students who enroll on edX.org have a huge choice of classes. The platform has 2 million learners in 196 countries with 4 million course enrollments. The service currently offers 157 courses in multiple languages -- English, French, Mandarin and Hindu -- at more than 44 institutions,

Classes can be taken at three levels of oversight: free on an audit basis, free with an honor code certificate of completion, or learners can pay and receive an ID-verified certificate by taking proctored exams. Whereas the free courses on edX have a pass rate of 5%, students who pay to take the ID-verified course have a pass rate of 60%. These students have skin in the game, Prof. Sarma said, and after the courses on exit interviews they say it was an incredible experience and that they learned something.

6.3. Business Model

edX was formed as a not-for-profit entity to bring learning to the masses. But, not-for-profit does not mean operating at a loss, Prof. Sarma said. People think that Google Maps is free, but actually Google operates it using a "freemium" model. Extensive users of Google Maps receive a bill from Google, as one MIT researcher did. The same is true for services like Dropbox. Similarly, although edX, operates as a not-for-profit, it licenses its courses to other schools and also sells digital textbooks. A business-to-nation model is also offered, in that nations such as France have asked to adopt the edX platform for the whole country. Finally, there is a philanthropic aspect, with foundations such as the Gates Foundation and the Hewlett Foundation donating to edX.

6.4. Democratization of Learning

MIT was founded in 1861 by William Barton Rogers. The term "technology" was about 30 years old at the time. Harvard was well-established but educated only upper class WASP males and taught memorization in Latin. MIT, on the other hand, emphasized both a professional and a liberal education. The institute admitted its first woman within 10 years of its founding, and the famous physicist Richard Feynman came to MIT because of religious quotas imposed at other schools. The move to online with edX is the next step in the democratization of learning. MIT is also engaged in outreach programs, designing BostonX and ChicagoX for those cities to reach all students, not just rich kids.

Prof. Sarma shared the story of Battushig Myanganbayar, a student in Mongolia, who wanted to build a traffic warning system for his sister. He learned about edX through his high school teacher and enrolled in MIT's Circuits and Electronics class on edX. Battushig aced the course, achieving a perfect score, and he is now enrolled in MIT's residential program. This remarkable story would have been possible without edX.

6.5. Advantages of Online Learning

Online learning also allows for instant feedback. In a traditional lecture, a student may learn a concept on Monday but not quite understand it. In a large class setting, the student may hesitate to ask a question, so he remains unsure. On Friday, homework is assigned that is then turned in the following week and graded a week later. Thus, the student does not have an opportunity to clarify the lecture material until three weeks after the lecture -- a long time from doubt to resolution during which misunderstandings can pile up. But online, the edX experience is designed so that students gain instant feedback. Weekly online quizzes are proctored, and students who are not satisfied with the grades they received can take the test again. As a result, students retake tests until they get 100% -- that's called mastery learning. With instant feedback, students know they are on the right track.

6.6. Relationship to MIT's Residential Program

Lectures are more efficient online, because professors must carefully plan them to ensure they cover the necessary concepts within the allotted time. Online lectures support MIT's residential program because instead of taking class time for lectures, the sessions can be viewed outside of class. As a result, class time can be used to provide the "magic" of lab work and discussion; the magic time when real learning takes place. Indeed, supplementing residential courses with online content, the interaction between students and teachers improves because without the burden of lectures the class time can be spent mainly on discussion and project work. MIT's founding tenet of "mens et manus" or "mind and hand" means learning by doing. The lab and workshop have been ever-present teaching environments at MIT, and the 27,000 companies that have grown out of MIT are testament to the importance of this hands-on approach to education.

The edX service is being adopted internally at MIT. The initial launch in the fall of 2012 started with 3 courses and 600 students. As of spring 2014, it's grown to 30 courses and 2318 students. MIT launched its first professional education class 1.5 months ago and already has 3500 signups.

Work remains to be done, however, as a task force found that online learning is not reaching as many women as it could. Also, although the program is reaching a wide economic cross-section aboard, its coverage in the US is narrower. Some fear that although the intent of edX is to democratize higher education, the effort could further deepen the wealth gap unless more outreach is done.

Finally, edX can be applied to corporate training and self-improvement as employees continually upgrade their skills.

7. Cross-Cutting Themes

From its founding days, MIT has stressed the merger "mind and hands" (mens et manus), with a focus on combining scientific knowledge and industrial practice. The presentations on data mining, robotics, and new 4-D printed materials clearly illustrated this intersection of the cerebral and the physical.

7.1. Human-Computer Integration

The presentations at Crossroads 2014 illustrated how people and computers are becoming more intertwined that ever before. By 2050, the world will have 50 billion devices connected to the Internet. In developed countries, many people today have dozens of Internet devices in their homes, in their cars, or on their persons. Ubiquitous smart phones with GPS, accelerometers, microphones and cameras are de facto ubiquitous sensors supporting all manner of applications and feeding big data repositories. That turns everyone and everything into a sensor network generating unprecedented volumes of data. These devices are now built into the fabric of our lives, societies, and supply chains.

But the devices do more than collect data; they also display data, thereby enabling the human-computer integration loop. Several of the presenters noted the key role of computer-based visualization as a crucial interface between machines and people. Presenters mentioned using visualization and computer graphics for looking at big data (Prof. Madden), creating compelling images to motivate decision makers (Dr. Sanchez), testing new factory automation (Prof. Shah), designing smart materials (Mr. Tibbits), and in the context of training (Prof. Sarma). For example, ultra-high-speed GPU (graphics processing unit) implementations of database searches can let people visualize and manipulate overwhelming volumes of data, such as a database of 100 million Tweets. Smarter ways to present data promotes more creative analytics and decision making.

7.2. Machines (and Materials) get Smarter

Integrating people and robots on the manufacturing floor offers the potential to combine robotic efficiency with human dexterity and artistry. Currently, safety concerns force the strict segregation of robots into caged areas, which limits the machines' usefulness on fast-flowing manufacturing lines. New sensors and systems could enable more mixing of people and machines. One of the previous limitations of allowing people into robotic work areas -- which may cause the robots to stop work for safety reasons -- was the effects of the interruption on scheduling. Prior schedulers required 30+ minutes to recalculate a complex sequence of robotic tasks. Prof. Shah described new scheduling algorithms that recalculate in seconds by borrowing scheduling techniques used in managing real-time computers.

Integrating people and robots also calls for new approaches to training..Without the right training, people are hesitant to move near working robots, and the machine's safety logic makes it hesitant to move near people, too. Cross-training is a very effective technique used by human teams, in which people switch roles to learn each other's jobs. Prof. Shah's lab research shows that the same is true with human-robot teams. People and robots can work together once they better understand each other's jobs.

Big data also poses big challenges for data scientists: the larger and more the data set, the more laborious the analysis. The most striking opportunities in Big Data lie not in assessing known relationships in the data but in finding unknown ones, such as why healthcare costs vary so much from person to person. Current methods depend exclusively on human genius to postulate and test hypotheses. Yet Prof. Madden noted that advances in predicate-free analysis might enable smarter computers to automatically uncover previously unknown relationships in physical, economic, and social systems.

Smarter ways to undertake familiar tasks could also transform key parts of the manufacturing process. Today, product assembly comprises a large portion of manufacturing costs; smart people (or smart robots) are required to assemble dumb materials into the final product. Mr. Tibbits showed how this problem might be turned on its head with smarter materials that self-assemble under unsophisticated manufacturing procedures, such as simply shaking a box of parts. Cleverly designed parts, which can be made with 3-D printing, can be shaped so that they fit together in only the right way.

With 4-D printing, parts can change shape over time in response to an activating energy or the environment. Mr. Tibbits demonstrated how a flat part that is easy to ship might automatically fold itself into a large complex structure when exposed to water at a location further along the supply chain. Another demonstration showed a part that fit into a 5" x 5" x 6" volume, unfolded into a 50 foot chain, and then could be easily refolded into a large and intricate chandelier. Bulky or delicate objects might be shipped in a compact state and then self-assembled at the customer site. Smart 4-D materials can also respond to their environment during use: one can imagine that in the future a shoe might have the capability to become cozy and waterproof in the cold and rain, but then become open and airy when it's hot and dry. Materials that respond to moisture, heat, light and other influences would be more versatile than their traditional counterparts. A single self-adaptive product might replace the need for many less-smart ones.

7.3. Brave New World

The presenters noted that technology has also created problems. Our highly-interconnected networks of devices are very insecure, Dr. Sanchez said. The least secure cell phone or network printer in an organization or household provides a backdoor for a major security breach. Anyone can buy software for breaking into people's computers or rent computer time for cracking passwords. Prof. Madden warned about the problems of Big Data inevitably including sensitive data about consumers -- their personal habits, medical issues, and other private information. Today's computing power can be turned against us to steal identities, purloin trade secrets, perpetrate fraud, or uncover things that people and companies don't want revealed about themselves. It's an age of potentially involuntary, malicious transparency.

At some level, technology can also help fix the problems created by technology. Encrypted database systems such as Monomi, described by Prof. Madden, create data storage environments where even the database owner can't breach the privacy of the personal information in the database. Moreover, all those smart phone sensors and Big Data processes can help security systems learn who (or which devices) can be trusted. A person's everyday habits and motions form a kind of signature that augments the traditional password. These sensor systems and network monitoring processes can also potentially sense suspicious outlier events, such as someone printing sensitive corporate documents at 5 a.m. to some other department's printer.

Disruptive technologies also mean disrupted employees in a hyper-competitive economic system, that no longer supports lifelong employment or engenders worker loyalty. Prof. Berger, Prof. Sarma, Prof. Madden, Dr. Sanchez, and Prof. Shah all cited the problem of skills gaps and the need for training. Networked technology and networked people can help solve this problem. Prof. Sarma talked about how MOOCs (Massive Open Online Courses) enable anyone to access top-quality education regardless of time-of-day or where they live. MOOCs use visualization and social media technology to give students more timely feedback and enable the scaling of a class from the traditional one-room lecture hall to a global environment with hundreds of thousands of collaboratively-participating students.

7.4 Supply Chains in the Crosshairs

The potential impacts of the disruptive technologies highlighted at Crossroads 2014 are wide-ranging. But as each speaker traced the likely development path of these innovations, it became apparent that supply chains could, in some way, be reshaped by them.

US industry needs to bridge some yawning gaps in the country's manufacturing ecosystem, problems that have a major affect on where future products will be made how they will be delivered. Supply chain managers are heavy consumers of Big Data, but there are some critical analytical challenges to overcome before the profession can harness the flood of data generated by the Internet of Things. Along the way, they must also find ways to protect massive databases from cyber attacks. Robots have been a feature of production lines for many years, but the new generation of machines is more closely integrated with human operators, and this high level of integration helps to make supply chains more responsive. Self-assembled products could transform product delivery channels. The online education revolution touches supply chains directly; in 2015 MIT will launch an online supply chain program with a global reach.

It is widely accepted that the pace of technological change has never been greater. Crossroads 2014 reinforced this belief, and showed that supply chain professionals need to keep abreast of new developments – even those that at first glance might appear to be largely irrelevant to them. Just as supply chains are interconnected globally, so disruptive innovations in tangential areas can cause ripples that disrupt supply chains.