Chapter 1

THE AUTOMATION WAVE

A warehouse worker approaches a stack of boxes. The boxes are of varying shapes, sizes, and colors, and they are stacked in a somewhat haphazard way.

Imagine for a moment that you can see inside the brain of the worker tasked with moving the boxes, and consider the complexity of the problem that needs to be solved.

Many of the boxes are a standard brown color and are pressed tightly against each other, making the edges difficult to perceive. Where precisely does one box end and the next begin? In other cases, there are gaps and misalignments. Some boxes are rotated so that one edge juts out. At the top of the pile, a small box rests at an angle in the space between two larger boxes. Most of the boxes are plain brown or white cardboard, but some are emblazoned with company logos, and a few are full-color retail boxes intended to be displayed on store shelves.

The human brain is, of course, capable of making sense of all this complicated visual information almost instantaneously. The worker easily perceives the dimensions and orientation of each box, and seems to know instinctively that he must begin by moving the boxes at the top of the stack and how to move the boxes in a sequence that won't destabilize the rest of the pile.

This is exactly the type of visual perception challenge that the human brain has evolved to overcome. That the worker succeeds in moving the boxes would be completely unremarkable—were it not for the fact that, in this case, the worker is a robot. To be more precise, it is a snake-like robotic arm, its head consisting of a suction-powered gripper. The robot is slower to comprehend than a human would be. It peers at the boxes, adjusts its gaze slightly, ponders some more, and then finally lunges forward and grapples a box from the top of the pile.* The sluggishness, however, results almost entirely from the staggering complexity of the computation required to perform this seemingly simple task. If there is one thing the history of information technology teaches, it is that this robot is going to very soon get a major speed upgrade.

Indeed, engineers at Industrial Perception, Inc., the Silicon Valley start-up company that designed and built the robot, believe the machine will ultimately be able to move a box every second. That compares with a human worker's maximum rate of a box roughly every six seconds.[1] Needless to say, the robot can work continuously; it will never get tired or suffer a back injury—and it will certainly never file a worker's compensation claim.

Industrial Perception's robot is remarkable because its capability sits at the nexus of visual perception, spatial computation, and dexterity. In other words, it is invading the final frontier of machine automation, where it will compete for the few relatively routine, manual jobs that are still available to human workers.

Robots in factories are, of course, nothing new. They have become indispensable in virtually every sector of manufacturing, from

* A video of Industrial Perception's box-moving robot can be seen on the company's website at http://www.industrial-perception.com/technology.html.

automobiles to semiconductors. Electric-car company Tesla's new plant in Fremont, California, uses 160 highly flexible industrial robots to assemble about 400 cars per week. As a new-car chassis arrives at the next position in the assembly line, multiple robots descend on it and operate in coordination. The machines are able to autonomously swap the tools wielded by their robotic arms in order to complete a variety of tasks. The same robot, for example, installs the seats, retools itself, and then applies adhesive and drops the windshield into place.[2] According to the International Federation of Robotics, global shipments of industrial robots increased by more than 60 percent between 2000 and 2012, with total sales of about $28 billion in 2012. By far the fastest-growing market is China, where robot installations grew at about 25 percent per year between 2005 and 2012.[3]

While industrial robots offer an unrivaled combination of speed, precision, and brute strength, they are, for the most part, blind actors in a tightly choreographed performance. They rely primarily on precise timing and positioning. In the minority of cases where robots have machine vision capability, they can typically see in just two dimensions and only in controlled lighting conditions. They might, for example, be able to select parts from a flat surface, but an inability to perceive depth in their field of view results in a low tolerance for environments that are to any meaningful degree unpredictable. The result is that a number of routine factory jobs have been left for people. Very often these are jobs that involve filling the gaps between the machines, or they are at the end points of the production process. Examples might include choosing parts from a bin and then feeding them into the next machine, or loading and unloading the trucks that move products to and from the factory.

The technology that powers the Industrial Perception robot's ability to see in three dimensions offers a case study in the ways that cross-fertilization can drive bursts of innovation in unexpected areas. It might be argued that the robot's eyes can trace their origin to November 2006, when Nintendo introduced its Wii video game console.

Nintendo's machine included an entirely new type of game controller: a wireless wand that incorporated an inexpensive device called an accelerometer. The accelerometer was able to detect motion in three dimensions and then output a data stream that could be interpreted by the game console. Video games could now be controlled through body movements and gestures. The result was a dramatically different game experience. Nintendo's innovation smashed the stereotype of the nerdy kid glued to a monitor and a joystick, and opened a new frontier for games as active exercise.

It also demanded a competitive response from the other major players in the video game industry. Sony Corporation, makers of the PlayStation, elected to essentially copy Nintendo's design and introduced its own motion-detecting wand. Microsoft, however, aimed to leapfrog Nintendo and come up with something entirely new. The Kinect add-on to the Xbox 360 game console eliminated the need for a controller wand entirely. To accomplish this, Microsoft built a webcam-like device that incorporates three-dimensional machine vision capability based in part on imaging technology created at a small Israeli company called PrimeSense. The Kinect sees in three dimensions by using what is, in essence, sonar at the speed of light: it shoots an infrared beam at the people and objects in a room and then calculates their distance by measuring the time required for the reflected light to reach its infrared sensor. Players could now interact with the Xbox game console simply by gesturing and moving in view of the Kinect's camera.

The truly revolutionary thing about the Kinect was its price. Sophisticated machine vision technology—which might previously have cost tens or even hundreds of thousands of dollars and required bulky equipment—was now available in a compact and lightweight consumer device priced at $150. Researchers working in robotics instantly realized the potential for the Kinect technology to transform their field. Within weeks of the product's introduction, both university-based engineering teams and do-it-yourself innovators had hacked into the Kinect and posted YouTube videos of robots that were now able to see in three dimensions.[4] Industrial Perception likewise decided to base its vision system on the technology that powers the Kinect, and the result is an affordable machine that is rapidly approaching a nearly human-level ability to perceive and interact with its environment while dealing with the kind of uncertainty that characterizes the real world.

A Versatile Robotic Worker

Industrial Perception's robot is a highly specialized machine focused specifically on moving boxes with maximum efficiency. Boston-based Rethink Robotics has taken a different track with Baxter, a lightweight humanoid manufacturing robot that can easily be trained to perform a variety of repetitive tasks. Rethink was founded by Rodney Brooks, one of the world's foremost robotics researchers at MIT and a co-founder of iRobot, the company that makes the Roomba automated vacuum cleaner as well as military robots used to defuse bombs in Iraq and Afghanistan. Baxter, which costs significantly less than a year's wages for a typical US manufacturing worker, is essentially a scaled-down industrial robot that is designed to operate safely in close proximity to people.

In contrast to industrial robots, which require complex and expensive programming, Baxter can be trained simply by moving its arms through the required motions. If a facility uses multiple robots, one Baxter can be trained and then the knowledge can be propagated to the others simply by plugging in a USB device. The robot can be adapted to a variety of tasks, including light assembly work, transferring parts between conveyer belts, packing products into retail packaging, or tending machines used in metal fabrication. Baxter is particularly talented at packing finished products into shipping boxes. K'NEX, a toy construction set manufacturer located in Hatfield, Pennsylvania, found that Baxter's ability to pack its products tightly allowed the company to use 20–40 percent fewer boxes.[5] Rethink's robot also has two-dimensional machine vision capability powered by cameras on both wrists and can pick up parts and even perform basic quality-control inspections.

The Coming Explosion in Robotics

While Baxter and Industrial Perception's box-moving robot are dramatically different machines, they are both built on the same fundamental software platform. ROS—or Robot Operating System—was originally conceived at Stanford University's Artificial Intelligence Laboratory and then developed into a full-fledged robotics platform by Willow Garage, Inc., a small company that designs and manufactures programmable robots that are used primarily by researchers at universities. ROS is similar to operating systems like Microsoft Windows, Macintosh OS, or Google's Android but is geared specifically toward making robots easy to program and control. Because ROS is free and also open source—meaning that software developers can easily modify and enhance it—it is rapidly becoming the standard software platform for robotics development.

The history of computing shows pretty clearly that once a standard operating system, together with inexpensive and easy-to-use programming tools, becomes available, an explosion of application software is likely to follow. This has been the case with personal computer software and, more recently, with iPhone, iPad, and Android apps. Indeed, these platforms are now so saturated with application software that it can be genuinely difficult to conceive of an idea that hasn't already been implemented.

It's a good bet that the field of robotics is poised to follow a similar path; we are, in all likelihood, at the leading edge of an explosive wave of innovation that will ultimately produce robots geared toward nearly every conceivable commercial, industrial, and consumer task. That explosion will be powered by the availability of standardized software and hardware building blocks that will make it a relatively simple matter to assemble new designs without the need to reinvent the wheel. Just as the Kinect made machine vision affordable, other hardware components—such as robotic arms—will see their costs driven down as robots begin scaling up to high-volume production. As of 2013, there were already thousands of software components available to work with ROS, and development platforms were cheap enough to allow nearly anyone to start designing new robotics applications. Willow Garage, for example, sells a complete mobile robot kit called TurtleBot that includes Kinect-powered machine vision for about $1,200. After inflation is taken into account, that's far less than what an inexpensive personal computer and monitor cost in the early 1990s, when Microsoft Windows was in the early stages of producing its own software explosion.

When I visited the RoboBusiness conference and tradeshow in Santa Clara, California, in October 2013, it was clear that the robotics industry had already started gearing up for the coming explosion. Companies of all sizes were on hand to showcase robots designed to perform precision manufacturing, transport medical supplies between departments in large hospitals, or autonomously operate heavy equipment for agriculture and mining. There was a personal robot named "Budgee" capable of carrying up to fifty pounds of stuff around the house or at the store. A variety of educational robots focused on everything from encouraging technical creativity to assisting children with autism or learning disabilities. At the Rethink Robotics booth, Baxter had received Halloween training and was grasping small boxes of candy and then dropping them into pumpkin-shaped trick-or-treat buckets. There were also companies marketing components like motors, sensors, vision systems, electronic controllers, and the specialized software used to construct robots. Silicon Valley start-up Grabit Inc. demonstrated an innovative electroadhesion-powered gripper that allows robots to pick up, carry, and place nearly anything simply by employing a controlled electrostatic charge. To round things out, a global law firm with a specialized robotics practice was on hand to help employers navigate the complexities of labor, employment, and safety regulations when robots are brought in to replace, or work in close proximity to, people.

One of the most remarkable sights at the tradeshow was in the aisles—which were populated by a mix of human attendees and dozens of remote-presence robots provided by Suitable Technologies, Inc. These robots, consisting of a flat screen and camera mounted on a mobile pedestal, allowed remote participants to visit tradeshow booths, view demonstrations, ask questions, and otherwise interact normally with other participants. Suitable Technologies offered remote presence at the tradeshow for a minimal fee, allowing visitors from outside the San Francisco Bay area to avoid thousands of dollars in travel costs. After a few minutes, the robots—each with a human face displayed on its screen—did not seem at all out of place as they prowled between booths and engaged other attendees in conversation.

Manufacturing Jobs and Factory Reshoring

In a September 2013 article, Stephanie Clifford of the *New York Times* told the story of Parkdale Mills, a textile factory in Gaffney, South Carolina. The Parkdale plant employs about 140 people. In 1980, the same level of production would have required more than 2,000 factory workers. Within the Parkdale plant, "only infrequently does a person interrupt the automation, mainly because certain tasks are still cheaper if performed by hand—like moving half-finished yarn between machines on forklifts."[6] Completed yarn is conveyed automatically toward packing and shipping machines along pathways attached to the ceiling.

Nonetheless, those 140 factory jobs represent at least a partial reversal of a decades-long decline in manufacturing employment. The

US textile industry was decimated in the 1990s as production moved to low-wage countries, especially China, India, and Mexico. About 1.2 million jobs—more than three-quarters of domestic employment in the textile sector—vanished between 1990 and 2012. The last few years, however, have seen a dramatic rebound in production. Between 2009 and 2012, US textile and apparel exports rose by 37 percent to a total of nearly $23 billion.[7] The turnaround is being driven by automation technology so efficient that it is competitive with even the lowest-wage offshore workers.

Within the manufacturing sector in the United States and other developed countries, the introduction of these sophisticated labor-saving innovations is having a mixed impact on employment. While factories like Parkdale don't directly create large numbers of manufacturing jobs, they do drive increased employment at suppliers and in peripheral areas like driving the trucks that move raw materials and finished products. While a robot like Baxter can certainly eliminate the jobs of some workers who perform routine tasks, it also helps make US manufacturing more competitive with low-wage countries. Indeed, there is now a significant "reshoring" trend under way, and this is being driven both by the availability of new technology and by rising offshore labor costs, especially in China where typical factory workers saw their pay increase by nearly 20 percent per year between 2005 and 2010. In April 2012, the Boston Consulting Group surveyed American manufacturing executives and found that nearly half of companies with sales exceeding $10 billion were either actively pursuing or considering bringing factories back to the United States.[8]

Factory reshoring dramatically decreases transportation costs and also provides many other advantages. Locating factories in close proximity to both consumer markets and product design centers allows companies to cut production lead times and be far more responsive to their customers. As automation becomes ever more flexible and sophisticated, it's likely that manufacturers will trend toward offering more customizable products—perhaps, for example, allowing customers to create unique designs or specify hard-to-find clothing sizes through easy-to-use online interfaces. Domestic automated production could then put a finished product into a customer's hands within days.

There is, however, one important caveat to the reshoring narrative. Even the relatively small number of new factory jobs now being created as a result of reshoring won't necessarily be around over the long term; as robots continue to get more capable and dexterous and as new technologies like 3D printing come into widespread use, it seems likely that many factories will eventually approach full automation. Manufacturing jobs in the United States currently account for well under 10 percent of total employment. As a result, manufacturing robots and reshoring are likely to have a fairly marginal impact on the overall job market.

The story will be very different in developing countries like China, where employment is far more focused in the manufacturing sector. In fact, advancing technology has already had a dramatic impact on Chinese factory jobs; between 1995 and 2002 China lost about 15 percent of its manufacturing workforce, or about 16 million jobs.[9] There is strong evidence to suggest that this trend is poised to accelerate. In 2012, Foxconn—the primary contract manufacturer of Apple devices—announced plans to eventually introduce up to a million robots in its factories. Taiwanese company Delta Electronics, Inc., a producer of power adapters, has recently shifted its strategy to focus on low-cost robots for precision electronics assembly. Delta hopes to offer a one-armed assembly robot for about $10,000—less than half the cost of Rethink's Baxter. European industrial robot manufacturers like ABB Group and Kuka AG are likewise investing heavily in the Chinese market and are currently building local factories to churn out thousands of robots per year.[10]

Increased automation is also likely to be driven by the fact that the interest rates paid by large companies in China are kept artificially low as a result of government policy. Loans are often rolled over continuously, so that the principal is never repaid. This makes capital investment extremely attractive even when labor costs are low and has been one of the primary reasons that investment now accounts for nearly half of China's GDP.[11] Many analysts believe that this artificially low cost of capital has caused a great deal of mal-investment throughout China, perhaps most famously the construction of "ghost cities" that appear to be largely unoccupied. By the same token, low capital costs may create a powerful incentive for big companies to invest in expensive automation, even in those cases where it does not necessarily make good business sense to do so.

One of the biggest challenges for a transition to robotic assembly in the Chinese electronics industry will be designing robots that are flexible enough to keep up with rapid product lifecycles. Foxconn, for example, maintains massive facilities where workers live onsite in dormitories. In order to accommodate aggressive production schedules, thousands of workers can be woken in the middle of the night and set immediately to work. That results in an astonishing ability to rapidly ramp up production or adjust to product design changes, but it also puts extreme pressure on workers—as evidenced by the near epidemic of suicides that occurred at Foxconn facilities in 2010. Robots, of course, have the ability to work continuously, and as they become more flexible and easier to train for new tasks, they will become an increasingly attractive alternative to human workers, even when wages are low.

The trend toward increased factory automation in developing countries is by no means limited to China. Clothing and shoe production, for example, continues to be one of the most labor-intensive sectors of manufacturing, and factories have been transitioning from China to even lower-wage countries like Vietnam and Indonesia. In June 2013, athletic-shoe manufacturer Nike announced that rising wages in Indonesia had negatively impacted its quarterly financial numbers. According to the company's chief financial officer, the long-term solution to that problem is going to be "engineering the labor out of the product."[12] Increased automation is also seen as a way to deflect criticism regarding the sweatshop-like environments that often exist in third-world garment factories.

The Service Sector: Where the Jobs Are

In the United States and other advanced economies, the major disruption will be in the service sector—which is, after all, where the vast majority of workers are now employed. This trend is already evident in areas like ATMs and self-service checkout lanes, but the next decade is likely to see an explosion of new forms of service sector automation, potentially putting millions of relatively low-wage jobs at risk.

San Francisco start-up company Momentum Machines, Inc., has set out to fully automate the production of gourmet-quality hamburgers. Whereas a fast food worker might toss a frozen patty onto the grill, Momentum Machines' device shapes burgers from freshly ground meat and then grills them to order—including even the ability to add just the right amount of char while retaining all the juices. The machine, which is capable of producing about 360 hamburgers per hour, also toasts the bun and then slices and adds fresh ingredients like tomatoes, onions, and pickles only after the order is placed. Burgers arrive assembled and ready to serve on a conveyer belt. While most robotics companies take great care to spin a positive tale when it comes to the potential impact on employment, Momentum Machines co-founder Alexandros Vardakostas is very forthright about the company's objective: "Our device isn't meant to make employees more efficient," he said. "It's meant to completely obviate them."[13] [*] The company estimates that the average fast food

* The company is not unaware of the potential impact its technology will have on jobs and, according to its website, plans to support a program that will offer discounted technical training to workers who are displaced.

restaurant spends about $135,000 per year on wages for employees who produce hamburgers and that the total labor cost for burger production for the US economy is about $9 billion annually.[14] Momentum Machines believes its device will pay for itself in less than a year, and it plans to target not just restaurants but also convenience stores, food trucks, and perhaps even vending machines. The company argues that eliminating labor costs and reducing the amount of space required in kitchens will allow restaurants to spend more on high-quality ingredients, enabling them to offer gourmet hamburgers at fast food prices.

Those burgers might sound very inviting, but they would come at a considerable cost. Millions of people hold low-wage, often part-time, jobs in the fast food and beverage industries. McDonald's alone employs about 1.8 million workers in 34,000 restaurants worldwide.[15] Historically, low wages, few benefits, and a high turnover rate have helped to make fast food jobs relatively easy to find, and fast food jobs, together with other low-skill positions in retail, have provided a kind of private sector safety net for workers with few other options: these jobs have traditionally offered an income of last resort when no better alternatives are available. In December 2013, the US Bureau of Labor Statistics ranked "combined food preparation and serving workers," a category that excludes waiters and waitresses in full-service restaurants, as one of the top employment sectors in terms of the number of job openings projected over the course of the decade leading up to 2022—with nearly half a million new jobs and another million openings to replace workers who leave the industry.[16]

In the wake of the Great Recession, however, the rules that used to apply to fast food employment are changing rapidly. In 2011, McDonald's launched a high-profile initiative to hire 50,000 new workers in a single day and received over a million applications—a ratio that made landing a McJob more of a statistical long shot than getting accepted at Harvard. While fast food employment was once dominated by young people looking for a part-time income while in school, the industry now employs far more mature workers who rely on the jobs as their primary income. Nearly 90 percent of fast food workers are twenty or older, and the average age is thirty-five.[17] Many of these older workers have to support families—a nearly impossible task at a median wage of just $8.69 per hour.

The industry's low wages and nearly complete lack of benefits have drawn intensive criticism. In October 2013, McDonald's was lambasted after an employee who called the company's financial help line was advised to apply for food stamps and Medicaid.[18] Indeed, an analysis by the Labor Center at the University of California, Berkeley, found that more than half of the families of fast food workers are enrolled in some type of public assistance program and that the resulting cost to US taxpayers is nearly $7 billion per year.[19]

When a spate of protests and ad hoc strikes at fast food restaurants broke out in New York and then spread to more than fifty US cities in the fall of 2013, the Employment Policies Institute, a conservative think tank with close ties to the restaurant and hotel industries, placed a full-page ad in the *Wall Street Journal* warning that "Robots Could Soon Replace Fast Food Workers Demanding a Higher Minimum Wage." While the ad was doubtless intended as a scare tactic, the reality is that—as the Momentum Machines device demonstrates—increased automation in the fast food industry is almost certainly inevitable. Given that companies like Foxconn are introducing robots to perform high-precision electronic assembly in China, there is little reason to believe that machines won't also eventually be serving up burgers, tacos, and lattes across the fast food industry.*

Japan's Kura sushi restaurant chain has already successfully pioneered an automation strategy. In the chain's 262 restaurants, robots

* Economists categorize fast food as part of the service sector; however, from a technical standpoint it is really closer to being a form of just-in-time manufacturing.

help make the sushi while conveyor belts replace waiters. To ensure freshness, the system keeps track of how long individual sushi plates have been circulating and automatically removes those that reach their expiration time. Customers order using touch panel screens, and when they are finished dining they place the empty dishes in a slot near their table. The system automatically tabulates the bill and then cleans the plates and whisks them back to the kitchen. Rather than employing store managers at each location, Kura uses centralized facilities where managers are able to remotely monitor nearly every aspect of restaurant operations. Kura's automation-based business model allows it to price sushi plates at just 100 yen (about $1), significantly undercutting its competitors.[20]

It's fairly easy to envision many of the strategies that have worked for Kura, especially automated food production and offsite management, eventually being adopted across the fast food industry. Some significant steps have already been taken in that direction; McDonalds, for example, announced in 2011 that it would install touch screen ordering systems at 7,000 of its European restaurants.[21] Once one of the industry's major players begins to gain significant advantages from increased automation, the others will have little choice but to follow suit. Automation will also offer the ability to compete on dimensions beyond lower labor costs. Robotic production might be viewed as more hygienic since fewer workers would come into contact with the food. Convenience, speed, and order accuracy would increase, as would the ability to customize orders. Once a customer's preferences were recorded at one restaurant, automation would make it a simple matter to consistently produce the same results at other locations.

Given all this, I think it is quite easy to imagine that a typical fast food restaurant may eventually be able to cut its workforce by 50 percent, or perhaps even more. At least in the United States, the fast food market is already so saturated that it seems very unlikely that new restaurants could make up for such a dramatic reduction in the number of workers required at each location. And this, of course, would mean that a great many of the job openings forecast by the Bureau of Labor Statistics might never materialize.

The other major concentration of low-wage service jobs is in the general retail sector. Economists at the Bureau of Labor Statistics rank "retail salesperson" second only to "registered nurse" as the specific occupation that will add the most jobs in the decade ending in 2020 and expect over 700,000 new jobs to be created.[22] Once again, however, technology has the potential to make the government projections seem optimistic. We can probably anticipate that three major forces will shape employment in the retail sector going forward.

The first will be the continuing disruption of the industry by online retailers like Amazon, eBay, and Netflix. The competitive advantage that online suppliers have over brick and mortar stores is already, of course, evident with the demise of major retail chains like Circuit City, Borders, and Blockbuster. Both Amazon and eBay are experimenting with same-day delivery in a number of US cities, with the objective of undermining one of the last major advantages that local retail stores still enjoy: the ability to provide immediate gratification after a purchase.

In theory, the encroachment of online retailers should not necessarily destroy jobs but, rather, would transition them from traditional retail settings to the warehouses and distribution centers used by the online companies. However, the reality is that once jobs move to a warehouse they become far easier to automate. Amazon purchased Kiva Systems, a warehouse robotics company in 2012. Kiva's robots, which look a bit like huge, roving hockey pucks, are designed to move materials within warehouses. Rather than having workers roam the aisles selecting items, a Kiva robot simply zips under an entire pallet or shelving unit, lifts it, and then brings it directly to the worker packing an order. The robots navigate autonomously using a grid laid out by barcodes attached to the floor and are used to automate warehouse operations at a variety of major retailers in addition to

Amazon, including Toys "R" Us, the Gap, Walgreens, and Staples.[23] A year after the acquisition, Amazon had about 1,400 Kiva robots in operation but had only begun the process of integrating the machines into its massive warehouses. One Wall Street analyst estimates that the robots will ultimately allow the company to cut its order fulfillment costs by as much as 40 percent.[24]

The Kroger Company, one of the largest grocery retailers in the United States, has also introduced highly automated distribution centers. Kroger's system is capable of receiving pallets containing large supplies of a single product from vendors and then disassembling them and creating new pallets containing a variety of different products that are ready to ship to stores. It is also able to organize the way that products are stacked on the mixed pallets in order to optimize the stocking of shelves once they arrive at stores. The automated warehouses completely eliminate the need for human intervention, except for loading and unloading the pallets onto trucks.[25] The obvious impact that these automated systems have on jobs has not been lost on organized labor, and the Teamsters Union has repeatedly clashed with Kroger, as well as other grocery retailers, over their introduction. Both the Kiva robots and Kroger's automated system do leave some jobs for people, and these are primarily in areas, such as packing a mixture of items for final shipment to customers, that require visual recognition and dexterity. Of course, these are the very areas in which innovations like Industrial Perception's box-moving robots are rapidly advancing the technical frontier.

The second transformative force is likely to be the explosive growth of the fully automated self-service retail sector—or, in other words, intelligent vending machines and kiosks. One study projects that the value of products and services vended in this market will grow from about $740 billion in 2010 to more than $1.1 trillion by 2015.[26] Vending machines have progressed far beyond dispensing sodas, snacks, and lousy instant coffee, and sophisticated machines that sell consumer electronics products like Apple's iPod and iPad are now common in airports and upscale hotels. AVT, Inc., one of the leading manufacturers of automated retail machines, claims that it can design a custom self-service solution for virtually any product. Vending machines make it possible to dramatically reduce three of the most significant costs incurred in the retail business: real estate, labor, and theft by customers and employees. In addition to providing 24-hour service, many of the machines include video screens and are able to offer targeted point-of-sale advertising that's geared toward enticing customers to purchase related products in much the same way that a human sales clerk might do. They can also collect customer email addresses and send receipts. In essence, the machines offer many of the advantages of online ordering, with the added benefit of instant delivery.

While the proliferation of vending machines and kiosks is certain to eliminate traditional retail sales jobs, these machines will also, of course, create jobs in areas like maintenance, restocking, and repair. The number of those new jobs, however, is likely to be more limited than you might expect. The latest-generation machines are directly connected to the Internet and provide a continuous stream of sales and diagnostic data; they are also specifically designed to minimize the labor costs associated with their operation.

In 2010, David Dunning was the regional operations supervisor responsible for overseeing the maintenance and restocking of 189 Redbox movie rental kiosks in the Chicago area.[27] Redbox has over 42,000 kiosks in the United States and Canada, typically located at convenience stores and supermarkets, and rents about 2 million videos per day.[28] Dunning managed the Chicago-area kiosks with a staff of just seven. Restocking the machines is highly automated; in fact, the most labor-intensive aspect of the job is swapping the translucent movie advertisements displayed on the kiosk—a process that typically takes less than two minutes for each machine. Dunning and his staff divide their time between the warehouse, where new movies arrive, and their cars and homes, where they are able to access and manage the machines via the Internet. The kiosks are designed from the ground up for remote maintenance. For example, if a machine jams it will report this immediately, and a technician can log in with his or her laptop computer, jiggle the mechanism, and fix the problem without the need to visit the site. New movies are typically released on Tuesdays, but the machines can be restocked at any time prior to that; the kiosk will automatically make the movies available for rental at the right time. That allows technicians to schedule restocking visits to avoid traffic.

While the jobs that Dunning and his staff have are certainly interesting and desirable, in number they are a fraction of what a traditional retail chain would create. The now-defunct Blockbuster, for example, once had dozens of stores in greater Chicago, each employing its own sales staff.[29] At its peak, Blockbuster had a total of about 9,000 stores and 60,000 employees. That works out to about seven jobs per store—roughly the same number that Redbox employed in the entire region serviced by Dunning's team.

The third major force likely to disrupt employment in the retail sector will be the introduction of increased automation and robotics into stores as brick and mortar retailers strive to remain competitive. The same innovations that are enabling manufacturing robots to advance the frontier in areas like physical dexterity and visual recognition will eventually allow retail automation to begin moving from warehouses into more challenging and varied environments like stocking shelves in stores. In fact, as far back as 2005, Walmart was already investigating the possibility of using robots that rove store aisles at night and automatically scan barcodes in order to track product inventories.[30]

At the same time, self-service checkout aisles and in-store information kiosks are sure to become easier to use, as well as more common. Mobile devices will also become an ever more important self-service tool. Future shoppers will rely more and more on their phones as a way to shop, pay, and get help and information about products while in traditional retail settings. The mobile disruption of retail is already under way. Walmart, for example, is testing an experimental program that allows shoppers to scan barcodes and then checkout and pay with their phones—completely avoiding long checkout lines.[31] Silvercar, a start-up rental car company, offers the capability to reserve and pick up a car without ever having to interact with a rental clerk; the customer simply scans a barcode to unlock the car and then drives away.[32] As natural language technology like Apple's Siri or even more powerful systems like IBM's Watson continue to advance and become more affordable, it's easy to imagine shoppers soon being able to ask their mobile devices for assistance in much the same way they might ask a store employee. The difference, of course, is that the customer will never have to wait for or hunt down the employee; the virtual assistant will always be instantly available and will rarely, if ever, give an inaccurate answer.

While many retailers may choose to bring automation into traditional retail configurations, others may instead elect to entirely redesign stores—perhaps, in essence, turning them into scaled-up vending machines. Stores of this type might consist of an automated warehouse with an attached showroom where customers could examine product samples and place orders. Orders might then be delivered directly to customers, or perhaps even loaded robotically into vehicles. Regardless of the specific technological path ultimately followed by the retail industry, it's difficult to imagine that the eventual result won't be more robots and machines—and significantly fewer jobs for people.

Cloud Robotics

One of the most important propellants of the robot revolution may turn out to be "cloud robotics"—or the migration of much of the intelligence that animates mobile robots into powerful, centralized computing hubs. Cloud robotics has been enabled by the dramatic acceleration in the rate at which data can be communicated; it is now possible to offload much of the computation required by advanced robotics into huge data centers while also giving individual robots access to network-wide resources. That, of course, makes it possible to build less expensive robots, since less onboard computational power and memory are required, and also allows for instant software upgrades across multiple machines. If one robot employs centralized machine intelligence to learn and adapt to its environment, then that newly acquired knowledge could become instantly available to any other machines accessing the system—making it easy to scale machine learning across large numbers of robots. Google announced support for cloud robotics in 2011 and provides an interface that allows robots to take advantage of all the services designed for Android devices.*

The impact of cloud robotics may be most dramatic in areas like visual recognition that require access to vast databases as well as powerful computational capability. Consider, for example, the enormous technical challenge involved in building a robot capable of performing a variety of housekeeping chores. A robotic maid tasked with clearing up the clutter in a room would need to be able to recognize an almost unlimited number of objects and then decide what to do with them. Each of those items might come in a variety of styles, be oriented in different ways, and perhaps even be somehow entangled with other objects. Compare that challenge to the one taken on by the Industrial Perception box-moving robot we met at the beginning of this chapter. While that robot's ability to discern and grasp individual boxes even when they are stacked in a careless way is an impressive achievement, it is still limited to, well, boxes. That's obviously a very long way from being able to recognize and manipulate virtually any object of any shape and in any configuration.

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* Google's strong interest in robotics was further demonstrated in 2013, when the company purchased eight robotics start-up companies over a six-month period. Among the companies acquired was Industrial Perception.

Building such comprehensive visual perception and recognition into an affordable robot poses a daunting challenge. Yet, cloud robotics offers at least a glimpse of the path that may eventually lead to a solution. Google introduced its "Goggles" feature for camera-equipped mobile devices in 2010 and has significantly improved the technology since then. This feature allows you to take a photo of things like landmark buildings, books, works of art, and commercial products and then have the system automatically recognize and retrieve information relevant to the photo. While building the ability to recognize nearly any object into a robot's onboard system would be extraordinarily difficult and expensive, it's fairly easy to imagine robots of the future recognizing the objects in their environment by accessing a vast centralized database of images similar to the one used by the Goggles system. The cloud-based image library could be updated continuously, and any robots with access to the system would get an instant upgrade to their visual recognition capability.

Cloud robotics is sure to be a significant driver of progress in building more capable robots, but it also raises important concerns, especially in the area of security. Aside from its uncomfortable similarity to "Skynet," the controlling machine intelligence in the *Terminator* movies starring Arnold Schwarzenegger, there is the much more practical and immediate issue of susceptibility to hacking or cyber attack. This will be an especially significant concern if cloud robotics someday takes on an important role in our transportation infrastructure. For example, if automated trucks and trains eventually move food and other critical supplies under centralized control, such a system might create extreme vulnerabilities. There is already great concern about the vulnerability of industrial machinery, and of vital infrastructure like the electrical grid, to cyber attack. That vulnerability was demonstrated by the Stuxnet worm that was created by the US and Israeli governments in 2010 to attack the centrifuges used in Iran's nuclear program. If, someday, important infrastructure components are dependent on centralized machine intelligence, those concerns could be raised to an entirely new level.

Robots in Agriculture

Of all the employment sectors that make up the US economy, agriculture stands out as the one that has already undergone the most dramatic transformation as a direct result of technological progress. Most of those new technologies were, of course, mechanical in nature and came long before the advent of advanced information technology. In the late nineteenth century, nearly half of all US workers were employed on farms; by 2000 that fraction had fallen below 2 percent. For crops like wheat, corn, and cotton that can be planted, maintained, and harvested mechanically, the human labor required per bushel of output is now nearly negligible in advanced countries. Many aspects of raising and managing livestock are also mechanized. For example, robotic milking systems are in common use on dairy farms, and in the United States, chickens are grown to standardized sizes so as to make them compatible with automated slaughtering and processing.

The remaining labor-intensive areas of agriculture are primarily geared toward picking delicate, high-value fruits and vegetables, as well as ornamental plants and flowers. As with other relatively routine, manual occupations, these jobs have so far been protected from mechanization primarily because they are highly dependent on visual perception and dexterity. Fruits and vegetables are easily damaged and often need to be selected based on color or softness. For a machine, visual recognition is a significant challenge: lighting conditions can be highly variable, and individual fruits can be in a variety of orientations and may be partly or even completely obscured by leaves.

The same innovations that are advancing the robotics frontier in factory and warehouse settings are finally making many of these remaining agricultural jobs susceptible to automation. Vision

Robotics, a company based in San Diego, California, is developing an octopus-like orange harvesting machine. The robot will use three-dimensional machine vision to make a computer model of an entire orange tree and then store the location of each fruit. That information will then be passed on to the machine's eight robotic arms, which will rapidly harvest the oranges.[33] Boston-area start-up Harvest Automation is initially focused on building robots to automate operations in nurseries and greenhouses; the company estimates that manual labor accounts for over 30 percent of the cost of growing ornamental plants. In the longer run, the company believes that its robots will be able to perform up to 40 percent of the manual agricultural labor now required in the United States and Europe.[34] Experimental robots are already pruning grapevines in France using machine vision technology combined with algorithms that decide which stems should be cut.[35] In Japan, a new machine is able to select ripe strawberries based on subtle color variations and then pick a strawberry every eight seconds—working continuously and doing most of the work at night.[36]

Advanced agricultural robots are especially attractive in countries that do not have access to low-wage, migrant labor. Australia and Japan, for example, are both island nations with rapidly aging workforces. Security considerations likewise make Israel a virtual island in terms of labor mobility. Many fruits and vegetables need to be harvested within a very small time window, so that a lack of available workers at just the right time can easily turn out to be a catastrophic problem.

Beyond reducing the need for labor, agricultural automation has enormous potential to make farming more efficient and far less resource-intensive. Computers have the ability to track and manage crops at a level of granularity that would be inconceivable for human workers. The Australian Centre for Field Robotics (ACFR) at the University of Sydney is focused on employing advanced agricultural robotics to help position Australia as a primary supplier of food for Asia's exploding population—in spite of the country's relative paucity of arable land and fresh water. ACFR envisions robots that continuously prowl fields taking soil samples around individual plants and then injecting just the right amount of water or fertilizer.[37] Precision application of fertilizer or pesticides to individual plants, or even to specific fruits growing on a tree, could potentially reduce the use of these chemicals by up to 80 percent, thereby dramatically decreasing the amount of toxic runoff that ultimately ends up fouling rivers, streams, and other bodies of water.[38] *

Agriculture in most developing countries is notoriously inefficient. The plots of land worked by families are often tiny, capital investment is minimal, and modern technology is unavailable. Even though farming techniques are labor-intensive, the land often has to support more people than are really necessary to cultivate it. As global population grows to 9 billion and beyond in the coming decades, there will be ever-increasing pressure to transition any and all available arable land into larger and more efficient farms that are capable of producing higher crop yields. Advancing agricultural technology will have a significant role to play, especially in countries where water is scarce and ecosystems have been damaged by overuse of chemicals. Increased mechanization, however, will also mean that the land will provide livelihoods for far fewer people. The historical norm has been for those excess workers to migrate to cities and industrial centers in search of factory work—but as we have seen, those factories are themselves going to be transformed by accelerating automation technology. In fact, it seems somewhat difficult to imagine how many developing countries will succeed in navigating these technological disruptions without running into significant unemployment crises.

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* Precision agriculture—or the ability to keep track of and manage individual plants or even fruits—is part of the "big data" phenomenon, a subject that we'll examine in more depth in Chapter 4.

In the United States, agricultural robotics has the potential to eventually throw a wrench into many of the fundamental assumptions that underlie immigration policy—an area that is already subject to intensely polarized politics. The impact is already evident in some areas that used to employ large numbers of farmworkers. In California, machines skirt around the daunting visual challenge of picking individual almonds by simply grasping the entire tree and violently shaking it. The almonds fall to the ground where they'll be harvested by a different machine. Many California farmers have transitioned from delicate crops like tomatoes to more robust nuts because they can be harvested mechanically. Overall agricultural employment in California fell by about 11 percent in the first decade of the twenty-first century, even as the total production of crops like almonds, which are compatible with automated farming techniques, has exploded.[39]

As robotics and advanced self-service technologies are increasingly deployed across nearly every sector of the economy, they will primarily threaten lower-wage jobs that require modest levels of education and training. These jobs, however, currently make up the vast majority of the new positions being generated by the economy—and the US economy needs to create something on the order of a million jobs per year just to tread water in the face of population growth. Even if we set aside the possibility of an actual reduction in the number of these jobs as new technologies emerge, any decline in the rate at which they are created will have dire, cumulative consequences for employment over the long run.

Many economists and politicians might be inclined to dismiss this as a problem. After all, routine, low-wage, low-skill jobs—at least in advanced economies—tend to be viewed as inherently undesirable, and when economists discuss the impact of technology on these kinds of jobs, you are very likely to encounter the phrase "freed up"—as in, workers who lose their low-skill jobs will be freed up to pursue more training and better opportunities. The fundamental assumption, of course, is that a dynamic economy like the United States will always be capable of generating sufficient higher-wage, higher-skill jobs to absorb all those newly freed up workers—given that they succeed in acquiring the necessary training.

That assumption rests on increasingly shaky ground. In the next two chapters we'll look at the impact that automation has already had on jobs and incomes in the United States and consider the characteristics that set information technology apart as a uniquely disruptive force. That discussion will provide a jumping-off point from which to delve into an unfolding story that is poised to upend the conventional wisdom about the types of jobs most likely to be automated and the viability of ever more education and training as a solution: the machines are coming for the high-wage, high-skill jobs as well.