1. THE PROBLEM OF EXTREME COMPLEXITY

Some time ago I read a case report in the *Annals of Thoracic Surgery* . It was, in the dry prose of a medical journal article, the story of a nightmare. In a small Austrian town in the Alps, a mother and father had been out on a walk in the woods with their three-year-old daughter. The parents lost sight of the girl for a moment and that was all it took. She fell into an icy fishpond. The parents frantically jumped in after her. But she was lost beneath the surface for thirty minutes before they finally found her on the pond bottom. They pulled her to the surface and got her to the shore. Following instructions from an emergency response team reached on their cell phone, they began cardiopulmonary resuscitation.

Rescue personnel arrived eight minutes later and took the first recordings of the girl's condition. She was unresponsive. She had no blood pressure or pulse or sign of breathing. Her body temperature was just 66 degrees. Her pupils were dilated and unreactive to light, indicating cessation of brain function. She was gone.

But the emergency technicians continued CPR anyway. A helicopter took her to the nearest hospital, where she was wheeled directly into an operating room, a member of the emergency crew straddling her on the gurney, pumping her chest. A surgical team got her onto a heart-lung bypass machine as rapidly as it could. The surgeon had to cut down through the skin of the child's right groin and sew one of the desk-size machine's silicone rubber tubes into her femoral vein to take the blood out of her, then another into her femoral artery to send the blood back. A perfusionist turned the pump on, and as he adjusted the oxygen and temperature and flow through the system, the clear tubing turned maroon with her blood. Only then did they stop the girl's chest compressions.

Between the transport time and the time it took to plug the machine into her, she had been lifeless for an hour and a half. By the two-hour mark, however, her body temperature had risen almost ten degrees, and her heart began to beat. It was her first organ to come back.

After six hours, the girl's core reached 98.6 degrees, normal body temperature. The team tried to shift her from the bypass machine to a mechanical ventilator, but the pond water and debris had damaged her lungs too severely for the oxygen pumped in through the breathing tube to reach her blood. So they switched her instead to an artificial-lung system known as ECMO—extracorporeal membrane oxygenation. To do this, the surgeons had to open her chest down the middle with a power saw and sew the lines to and from the portable ECMO unit directly into her aorta and her beating heart.

The ECMO machine now took over. The surgeons removed the heart-lung bypass machine tubing. They repaired the vessels and closed her groin incision. The surgical team moved the girl into intensive care, with her chest still open and covered with sterile plastic foil. Through the day and night, the intensive care unit team worked on suctioning the water and debris from her lungs with a fiberoptic bronchoscope. By the next day, her lungs had recovered sufficiently for the team to switch her from ECMO to a mechanical ventilator, which required taking her back to the operating room to unplug the tubing, repair the holes, and close her chest.

Over the next two days, all the girl's organs recovered—her liver, her kidneys, her intestines, everything except her brain. A CT scan showed global brain swelling, which is a sign of diffuse damage, but no actual dead zones. So the team escalated the care one step further. It drilled a hole into the girl's skull, threaded a probe into the brain to monitor the pressure, and kept that pressure tightly controlled through constant adjustments in her fluids and medications. For more than a week, she lay comatose. Then, slowly, she came back to life.

First, her pupils started to react to light. Next, she began to breathe on her own. And, one day, she simply awoke. Two weeks after her accident, she went home. Her right leg and left arm were partially paralyzed. Her speech was thick and slurry. But she underwent extensive outpatient therapy. By age five, she had recovered her faculties completely. Physical and neurological examinations were normal. She was like any little girl again.

What makes this recovery astounding isn't just the idea that someone could be brought back after two hours in a state that would once have been considered death. It's also the idea that a group of people in a random hospital could manage to pull off something so enormously complicated. Rescuing a drowning victim is nothing like it looks on television shows, where a few chest compressions and some mouth-to-mouth resuscitation always seem to bring someone with waterlogged lungs and a stilled heart coughing and sputtering back to life. To save this one child, scores of people had to carry out thousands of steps correctly: placing the heart-pump tubing into her without letting in air bubbles; maintaining the sterility of her lines, her open chest, the exposed fluid in her brain; keeping a temperamental battery of machines up and running. The degree of difficulty in any one of these steps is substantial. Then you must add the difficulties of orchestrating them in the right sequence, with nothing dropped, leaving some room for improvisation, but not too much.

For every drowned and pulseless child rescued, there are scores more who don't make it—and not just because their bodies are too far gone. Machines break down; a team can't get moving fast enough; someone fails to wash his hands and an infection takes hold. Such cases don't get written up in the *Annals of Thoracic Surgery* , but they are the norm, though people may not realize it.

I think we have been fooled about what we can expect from medicine—fooled, one could say, by penicillin. Alexander Fleming's 1928 discovery held out a beguiling vision of health care and how it would treat illness or injury in the future: a simple pill or injection would be capable of curing not just one condition but perhaps many. Penicillin, after all, seemed to be effective against an astonishing variety of previously untreatable infectious diseases. So why not a similar cure-all for the different kinds of cancer? And why not something equally simple to melt away skin burns or to reverse cardiovascular disease and strokes?

Medicine didn't turn out this way, though. After a century of incredible discovery, most diseases have proved to be far more particular and difficult to treat. This is true even for the infections doctors once treated with penicillin: not all bacterial strains were susceptible and those that were soon developed resistance. Infections today require highly individualized treatment, sometimes with multiple therapies, based on a given strain's pattern of anti-biotic susceptibility, the condition of the patient, and which organ systems are affected. The model of medicine in the modern age seems less and less like penicillin and more and more like what was required for the girl who nearly drowned. Medicine has become the art of managing extreme complexity—and a test of whether such complexity can, in fact, be humanly mastered.

The ninth edition of the World Health Organization's international classification of diseases has grown to distinguish more than thirteen thousand different diseases, syndromes, and types of injury—more than thirteen thousand different ways, in other words, that the body can fail. And, for nearly all of them, science has given us things we can do to help. If we cannot cure the disease, then we can usually reduce the harm and misery it causes. But for each condition the steps are different and they are almost never simple. Clinicians now have at their disposal some six thousand drugs and four thousand medical and surgical procedures, each with different requirements, risks, and considerations. It is a lot to get right.

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There is a community clinic in Boston's Kenmore Square affiliated with my hospital. The word *clinic* makes the place sound tiny, but it's nothing of the sort. Founded in 1969, and now called Harvard Vanguard, it aimed to provide people with the full range of outpatient medical services they might need over the course of their lives. It has since tried to stick with that plan, but doing so hasn't been easy. To keep up with the explosive growth in medical capabilities, the clinic has had to build more than twenty facilities and employ some six hundred doctors and a thousand other health professionals covering fifty-nine specialties, many of which did not exist when the clinic first opened. Walking the fifty steps from the fifth-floor elevator to the general surgery department, I pass offices for general internal medicine, endocrinology, genetics, hand surgery, laboratory testing, nephrology, ophthalmology, orthopedics, radiology scheduling, and urology—and that's just one hallway.

To handle the complexity, we've split up the tasks among various specialties. But even divvied up, the work can become overwhelming. In the course of one day on general surgery call at the hospital, for instance, the labor floor asked me to see a twenty-five-year-old woman with mounting right lower abdominal pain, fever, and nausea, which raised concern about appendicitis, but she was pregnant, so getting a CT scan to rule out the possibility posed a risk to the fetus. A gynecological oncologist paged me to the operating room about a woman with an ovarian mass that upon removal appeared to be a metastasis from pancreatic cancer; my colleague wanted me to examine her pancreas and decide whether to biopsy it. A physician at a nearby hospital phoned me to transfer a patient in intensive care with a large cancer that had grown to obstruct her kidneys and bowel and produce bleeding that they were having trouble controlling. Our internal medicine service called me to see a sixty-one-year-old man with emphysema so severe he had been refused hip surgery because of insufficient lung reserves; now he had a severe colon infection—an acute diverticulitis—that had worsened despite three days of antibiotics, and surgery seemed his only option. Another service asked for help with a fifty-two-year-old man with diabetes, coronary artery disease, high blood pressure, chronic kidney failure, severe obesity, a stroke, and now a strangulating groin hernia. And an internist called about a young, otherwise healthy woman with a possible rectal abscess to be lanced.

Confronted with cases of such variety and intricacy—in one day, I'd had six patients with six completely different primary medical problems and a total of twenty-six different additional diagnoses—it's tempting to believe that no one else's job could be as complex as mine. But extreme complexity is the rule for almost everyone. I asked the people in Harvard Vanguard's medical records department if they would query the electronic system for how many different kinds of patient problems the average doctor there sees annually. The answer that came back flabbergasted me. Over the course of a year of office practice—which, by definition, excludes the patients seen in the hospital—physicians each evaluated an average of 250 different primary diseases and conditions. Their patients had more than nine hundred other active medical problems that had to be taken into account. The doctors each prescribed some three hundred medications, ordered more than a hundred different types of laboratory tests, and performed an average of forty different kinds of office procedures—from vaccinations to setting fractures.

Even considering just the office work, the statistics still didn't catch all the diseases and conditions. One of the most common diagnoses, it turned out, was "Other." On a hectic day, when you're running two hours behind and the people in the waiting room are getting irate, you may not take the time to record the precise diagnostic codes in the database. But, even when you do have the time, you commonly find that the particular diseases your patients have do not actually exist in the computer system.

The software used in most American electronic records has not managed to include all the diseases that have been discovered and distinguished from one another in recent years. I once saw a patient with a ganglioneuroblastoma (a rare type of tumor of the adrenal gland) and another with a nightmarish genetic condition called Li-Fraumeni syndrome, which causes inheritors to develop cancers in organs all over their bodies. Neither disease had yet made it into the pull-down menus. All I could record was, in so many words, “Other.” Scientists continue to report important new genetic findings, subtypes of cancer, and other diagnoses—not to mention treatments—almost weekly. The complexity is increasing so fast that even the computers cannot keep up.

But it’s not only the breadth and quantity of knowledge that has made medicine complicated. It is also the execution—the practical matter of what knowledge requires clinicians to do. The hospital is where you see just how formidable the task can be. A prime example is the place the girl who nearly drowned spent most of her recovery—the intensive care unit.

It’s an opaque term, *intensive care* . Specialists in the field prefer to call what they do *critical care* , but that still doesn’t exactly clarify matters. The nonmedical term *life support* gets us closer. The damage that the human body can survive these days is as awesome as it is horrible: crushing, burning, bombing, a burst aorta, a ruptured colon, a massive heart attack, rampaging infection. These maladies were once uniformly fatal. Now survival is commonplace, and a substantial part of the credit goes to the abilities intensive care units have developed to take artificial control of failing bodies. Typically, this requires a panoply of technology—a mechanical ventilator and perhaps a tracheostomy tube if the lungs have failed, an aortic balloon pump if the heart has given out, a dialysis machine if the kidneys don’t work. If you are unconscious and can’t eat, silicone tubing can be surgically inserted into your stomach or intestines for formula feeding. If your intestines are too damaged, solutions of amino acids, fatty acids, and glucose can be infused directly into your bloodstream.

On any given day in the United States alone, some ninety thousand people are admitted to intensive care. Over a year, an estimated five million Americans will be, and over a normal lifetime nearly all of us will come to know the glassed bay of an ICU from the inside. Wide swaths of medicine now depend on the life support systems that ICUs provide: care for premature infants; for victims of trauma, strokes, and heart attacks; for patients who have had surgery on their brains, hearts, lungs, or major blood vessels. Critical care has become an increasingly large portion of what hospitals do. Fifty years ago, ICUs barely existed. Now, to take a recent random day in my hospital, 155 of our almost 700 patients are in intensive care. The average stay of an ICU patient is four days, and the survival rate is 86 percent. Going into an ICU, being put on a mechanical ventilator, having tubes and wires run into and out of you, is not a sentence of death. But the days will be the most precarious of your life.

Fifteen years ago, Israeli scientists published a study in which engineers observed patient care in ICUs for twenty-four-hour stretches. They found that the average patient required 178 individual actions per day, ranging from administering a drug to suctioning the lungs, and every one of them posed risks. Remarkably, the nurses and doctors were observed to make an error in just 1 percent of these actions—but that still amounted to an average of two errors a day with every patient. Intensive care succeeds only when we hold the odds of doing harm low enough for the odds of doing good to prevail. This is hard. There are dangers simply in lying unconscious in bed for a few days. Muscles atrophy. Bones lose mass. Pressure ulcers form. Veins begin to clot. You have to stretch and exercise patients' flaccid limbs daily to avoid contractures; you have to give subcutaneous injections of blood thinners at least twice a day, turn patients in bed every few hours, bathe them and change their sheets without knocking out a tube or a line, brush their teeth twice a day to avoid pneumonia from bacterial buildup in their mouths. Add a ventilator, dialysis, and the care of open wounds, and the difficulties only accumulate.

The story of one of my patients makes the point. Anthony DeFilippo was a forty-eight-year-old limousine driver from Everett, Massachusetts, who started to hemorrhage at a community hospital during surgery for a hernia and gallstones. The surgeon was finally able to stop the bleeding but DeFilippo's liver was severely damaged, and over the next few days he became too sick for the hospital's facilities. I accepted him for transfer in order to stabilize him and figure out what to do. When he arrived in our ICU, at 1:30 a.m. on a Sunday, his ragged black hair was plastered to his sweaty forehead, his body was shaking, and his heart was racing at 114 beats a minute. He was delirious from fever, shock, and low oxygen levels .

"I need to get out!" he cried. "I need to get out!" He clawed at his gown, his oxygen mask, the dressings covering his abdominal wound.

"Tony, it's all right," a nurse said to him. "We're going to help you. You're in a hospital."

He shoved her out of the way—he was a big man—and tried to swing his legs out of the bed. We turned up his oxygen flow, put his wrists in cloth restraints, and tried to reason with him. He eventually tired out and let us draw blood and give him antibiotics.

The laboratory results came back showing liver failure and a steeply elevated white blood cell count, indicating infection. It soon became evident from his empty urine bag that his kidneys had failed, too. In the next few hours, his blood pressure fell, his breathing worsened, and he drifted from agitation to near unconsciousness. Each of his organ systems, including his brain, was shutting down.

I called his sister, his next of kin, and told her the situation. "Do everything you can," she said.

So we did. We gave him a syringeful of anesthetic, and a resident slid a breathing tube into his throat. Another resident "lined him up." She inserted a thin two-inch-long needle and catheter through his upturned right wrist and into his radial artery, then sewed the line to his skin with a silk suture. Next, she put in a central line—a twelve-inch catheter pushed into the jugular vein in his left neck. After she sewed that in place, and an X-ray showed its tip floating just where it was supposed to—inside his vena cava at the entrance to his heart—she put a third, slightly thicker line, for dialysis, through his right upper chest and into the subclavian vein, deep under the collarbone .

We hooked a breathing tube up to a hose from a ventilator and set it to give him fourteen forced breaths of 100 percent oxygen every minute. We dialed the ventilator pressures and gas flow up and down, like engineers at a control panel, until we got the blood levels of oxygen and carbon dioxide where we wanted them. The arterial line gave us continuous arterial blood pressure measurements, and we tweaked his medications to get the pressures we liked. We regulated his intravenous fluids according to venous pressure measurements from his jugular line. We plugged his subclavian line into tubing from a dialysis machine, and every few minutes his entire blood volume washed through this artificial kidney and back into his body; a little adjustment here and there, and we could alter the levels of potassium and bicarbonate and salt, as well. He was, we liked to imagine, a simple machine in our hands.

But he wasn't, of course. It was as if we had gained a steering wheel and a few gauges and controls, but on a runaway 18-wheeler hurtling down a mountain. Keeping that patient's blood pressure normal required gallons of intravenous fluid and a pharmacy shelf of drugs. He was on near-maximal ventilator support. His temperature climbed to 104 degrees. Less than 5 percent of patients with DeFilippo's degree of organ failure make it home. A single misstep could easily erase those slender chances.

For ten days, though, we made progress. DeFilippo's chief problem had been liver damage from his prior operation: the main duct from his liver was severed and was leaking bile, which is caustic—it digests the fat in one's diet and was essentially eating him alive from the inside. He had become too sick to survive an operation to repair the leak. So once we had stabilized him, we tried a temporary solution—we had radiologists place a plastic drain, using CT guidance, through his abdominal wall and into the severed duct in order to draw out the leaking bile. They found so much that they had to place three drains—one inside the duct and two around it. But, as the bile drained out, his fevers subsided. His need for oxygen and fluids diminished, and his blood pressure returned to normal. He was beginning to mend. Then, on the eleventh day, just as we were getting ready to take him off the ventilator, he again developed high, spiking fevers, his blood pressure sank, and his blood-oxygen levels plummeted again. His skin became clammy. He got shaking chills.

We couldn't understand what had happened. He seemed to have developed an infection, but our X-rays and CT scans failed to turn up a source. Even after we put him on four antibiotics, he continued to spike fevers. During one fever, his heart went into fibrillation. A Code Blue was called. A dozen nurses and doctors raced to his bedside, slapped electric paddles onto his chest, and shocked him. His heart responded and went back into rhythm. It took two more days for us to figure out what had gone wrong. We considered the possibility that one of his lines had become infected, so we put in new lines and sent the old ones to the lab for culturing. Forty-eight hours later, the results returned. All the lines were infected. The infection had probably started in one line, which perhaps was contaminated during insertion, and spread through DeFilippo's bloodstream to the others. Then they all began spilling bacteria into him, producing the fevers and steep decline.

This is the reality of intensive care: at any point, we are as apt to harm as we are to heal. Line infections are so common that they are considered a routine complication. ICUs put five million lines into patients each year, and national statistics show that after ten days 4 percent of those lines become infected. Line infections occur in eighty thousand people a year in the United States and are fatal between 5 and 28 percent of the time, depending on how sick one is at the start. Those who survive line infections spend on average a week longer in intensive care. And this is just one of many risks. After ten days with a urinary catheter, 4 percent of American ICU patients develop a bladder infection. After ten days on a ventilator, 6 percent develop bacterial pneumonia, resulting in death 40 to 45 percent of the time. All in all, about half of ICU patients end up experiencing a serious complication, and once that occurs the chances of survival drop sharply.

It was another week before DeFilippo recovered sufficiently from his infections to come off the ventilator and two months before he left the hospital. Weak and debilitated, he lost his limousine business and his home, and he had to move in with his sister. The tube draining bile still dangled from his abdomen; when he was stronger, I was going to have to do surgery to reconstruct the main bile duct from his liver. But he survived. Most people in his situation do not.

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Here, then, is the fundamental puzzle of modern medical care: you have a desperately sick patient and in order to have a chance of saving him you have to get the knowledge right and then you have to make sure that the 178 daily tasks that follow are done correctly—despite some monitor's alarm going off for God knows what reason, despite the patient in the next bed crashing, despite a nurse poking his head around the curtain to ask whether someone could help "get this lady's chest open." There is complexity upon complexity. And even specialization has begun to seem inadequate. So what do you do?

The medical profession's answer has been to go from specialization to superspecialization. I told DeFilippo's ICU story, for instance, as if I were the one tending to him hour by hour. That, however, was actually an intensivist (as intensive care specialists like to be called). As a general surgeon, I like to think I can handle most clinical situations. But, as the intricacies involved in intensive care have grown, responsibility has increasingly shifted to superspecialists. In the past decade, training programs focusing on critical care have opened in most major American and European cities, and half of American ICUs now rely on superspecialists.

Expertise is the mantra of modern medicine. In the early twentieth century, you needed only a high school diploma and a one-year medical degree to practice medicine. By the century's end, all doctors had to have a college degree, a four-year medical degree, and an additional three to seven years of residency training in an individual field of practice—pediatrics, surgery, neurology, or the like. In recent years, though, even this level of preparation has not been enough for the new complexity of medicine. After their residencies, most young doctors today are going on to do fellowships, adding one to three further years of training in, say, laparoscopic surgery, or pediatric metabolic disorders, or breast radiology, or critical care. A young doctor is not so young nowadays; you typically don't start in independent practice until your midthirties.

We live in the era of the superspecialist—of clinicians who have taken the time to practice, practice, practice at one narrow thing until they can do it better than anyone else. They have two advantages over ordinary specialists: greater knowledge of the details that matter and a learned ability to handle the complexities of the particular job. There are degrees of complexity, though, and medicine and other fields like it have grown so far beyond the usual kind that avoiding daily mistakes is proving impossible even for our most superspecialized.

There is perhaps no field that has taken specialization further than surgery. Think of the operating room as a particularly aggressive intensive care unit. We have anesthesiologists just to handle pain control and patient stability, and even they have divided into subcategories. There are pediatric anesthesiologists, cardiac anesthesiologists, obstetric anesthesiologists, neurosurgical anesthesiologists, and many others. Likewise, we no longer have just "operating room nurses." They too are often subspecialized for specific kinds of cases.

Then of course there are the surgeons. Surgeons are so absurdly ultraspecialized that when we joke about right ear surgeons and left ear surgeons, we have to check to be sure they don't exist. I am trained as a general surgeon but, except in the most rural places, there is no such thing. You really can't do everything anymore. I decided to center my practice on surgical oncology—cancer surgery—but even this proved too broad. So, although I have done all I can to hang on to a broad span of general surgical skills, especially for emergencies, I've developed a particular expertise in removing cancers of endocrine glands.

The result of the recent decades of ever-refined specialization has been a spectacular improvement in surgical capability and success. Where deaths were once a double-digit risk of even small operations, and prolonged recovery and disability was the norm, day surgery has become commonplace .

Yet given how much surgery is now done—Americans today undergo an average of seven operations in their lifetime, with surgeons performing more than fifty million operations annually—the amount of harm remains substantial. We continue to have upwards of 150,000 deaths following surgery every year—more than three times the number of road traffic fatalities. Moreover, research has consistently showed that at least half our deaths and major complications are avoidable. The knowledge exists. But however supremely specialized and trained we may have become, steps are still missed. Mistakes are still made.

3. THE END OF THE MASTER BUILDER

Four generations after the first aviation checklists went into use, a lesson is emerging: checklists seem able to defend anyone, even the experienced, against failure in many more tasks than we realized. They provide a kind of cognitive net. They catch mental flaws inherent in all of us—flaws of memory and attention and thoroughness. And because they do, they raise wide, unexpected possibilities.

But they presumably have limits, as well. So a key step is to identify which kinds of situations checklists can help with and which ones they can't.

Two professors who study the science of complexity—Brenda Zimmerman of York University and Sholom Glouberman of the University of Toronto—have proposed a distinction among three different kinds of problems in the world: the simple, the complicated, and the complex. Simple problems, they note, are ones like baking a cake from a mix. There is a recipe. Sometimes there are a few basic techniques to learn. But once these are mastered, following the recipe brings a high likelihood of success.

Complicated problems are ones like sending a rocket to the moon. They can sometimes be broken down into a series of simple problems. But there is no straightforward recipe. Success frequently requires multiple people, often multiple teams, and specialized expertise. Unanticipated difficulties are frequent. Timing and coordination become serious concerns.

Complex problems are ones like raising a child. Once you learn how to send a rocket to the moon, you can repeat the process with other rockets and perfect it. One rocket is like another rocket. But not so with raising a child, the professors point out. Every child is unique. Although raising one child may provide experience, it does not guarantee success with the next child. Expertise is valuable but most certainly not sufficient. Indeed, the next child may require an entirely different approach from the previous one. And this brings up another feature of complex problems: their outcomes remain highly uncertain. Yet we all know that it is possible to raise a child well. It’s complex, that’s all.

Thinking about averting plane crashes in 1935, or stopping infections of central lines in 2003, or rescuing drowning victims today, I realized that the key problem in each instance was essentially a simple one, despite the number of contributing factors. One needed only to focus attention on the rudder and elevator controls in the first case, to maintain sterility in the second, and to be prepared for cardiac bypass in the third. All were amenable, as a result, to what engineers call “forcing functions”: relatively straightforward solutions that force the necessary behavior—solutions like checklists.

We are besieged by simple problems. In medicine, these are the failures to don a mask when putting in a central line or to recall that one of the ten causes of a flat-line cardiac arrest is a potassium overdose. In legal practice, these are the failures to remember all the critical avenues of defense in a tax fraud case or simply the various court deadlines. In police work, these are the failures to conduct an eyewitness lineup properly, forgetting to tell the witness that the perpetrator of the crime may not be in the lineup, for instance, or having someone present who knows which one the suspect is. Checklists can provide protection against such elementary errors.

Much of the most critical work people do, however, is not so simple. Putting in a central line is just one of the 178 tasks an ICU team must coordinate and execute in a day—ICU work is complicated—and are we really going to be able to create and follow checklists for every possible one of them? Is this even remotely practical? There is no straightforward recipe for the care of ICU patients. It requires multiple practitioners orchestrating different combinations of tasks for different conditions—matters that cannot be controlled by simple forcing functions.

Plus, people are individual in ways that rockets are not—they are complex. No two pneumonia patients are identical. Even with the same bacteria, the same cough and shortness of breath, the same low oxygen levels, the same antibiotic, one patient might get better and the other might not. A doctor must be prepared for unpredictable turns that checklists seem completely unsuited to address. Medicine contains the entire range of problems—the simple, the complicated, *and* the complex—and there are often times when a clinician has to just do what needs to be done. Forget the paperwork. Take care of the patient.

I have been thinking about these matters for a long time now. I want to be a good doctor for my patients. And the question of when to follow one's judgment and when to follow protocol is central to doing the job well—or to doing anything else that is hard. You want people to make sure to get the stupid stuff right. Yet you also want to leave room for craft and judgment and the ability to respond to unexpected difficulties that arise along the way. The value of checklists for simple problems seems self-evident. But can they help avert failure when the problems combine everything from the simple to the complex?

I happened across an answer in an unlikely place. I found it as I was just strolling down the street one day.

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It was a bright January morning in 2007. I was on my way to work, walking along the sidewalk from the parking lot to the main entrance of my hospital, when I came upon a new building under construction for our medical center. It was only a skeleton of steel beams at that point, but it stretched eleven stories high, occupied a full city block, and seemed to have arisen almost overnight from the empty lot that had been there. I stood at one corner watching a construction worker welding a joint as he balanced on a girder four stories above me. And I wondered: How did he and all his co-workers know that they were building this thing right? How could they be sure that it wouldn't fall down?

The building was not unusually large. It would provide 150 private hospital beds (so we could turn our main tower's old, mostly shared rooms into private beds as well) and sixteen fancy new operating rooms (which I was especially looking forward to)—nothing out of the ordinary. I would bet that in the previous year dozens of bigger buildings had been constructed around the country.

Still, this one was no small undertaking, as the hospital's real estate manager later told me. The building, he said, would be 350,000 square feet in size, with three stories underground in addition to the eleven stories above. It would cost $360 million, fully delivered, and require 3,885 tons of steel, thirteen thousand yards of concrete, nineteen air handling units, sixteen elevators, one cooling tower, and one backup emergency generator. The construction workers would have to dig out 100,000 cubic yards of dirt and install 64,000 feet of copper piping, forty-seven miles of conduit, and ninety-five miles of electrical wire—enough to reach Maine.

And, oh yeah, I thought to myself, this thing couldn't fall down.

When I was eleven years old, growing up in Athens, Ohio, I decided I was going to build myself a bookcase. My mother gave me ten dollars, and I biked down to the C&E Hardware store on Richland Avenue. With the help of the nice man with hairy ears behind the counter, I bought four pine planks, each eight inches wide and three-quarters of an inch thick and cut to four feet long. I also bought a tin of stain, a tin of varnish, some sandpaper, and a box of common nails. I lugged the stuff home to our garage. I carefully measured my dimensions. Then I nailed the two cross planks into the two side planks and stood my new bookcase up. It looked perfect. I sanded down the surfaces, applied the stain and soon the varnish. I took it to my bedroom and put a half dozen books on it. Then I watched the whole thing fall sideways like a drunk tipping over. The two middle boards began pulling out. So I hammered in a few more nails and stood the bookcase up again. It tipped over the other way. I banged in some more nails, this time coming in at an angle, thinking that would do the trick. It didn't. Finally, I just nailed the damn thing directly into the wall. And that was how I discovered the concept of bracing.

So as I looked up at this whole building that had to stand up straight even in an earthquake, puzzling over how the workers could be sure they were constructing it properly, I realized the question had two components. First, how could they be sure that they had the right knowledge in hand? Second, how could they be sure that they were applying this knowledge correctly?

Both aspects are tricky. In designing a building, experts must take into account a disconcertingly vast range of factors: the makeup of the local soil, the desired height of the individual structure, the strength of the materials available, and the geometry, to name just a few. Then, to turn the paper plans into reality, they presumably face equally byzantine difficulties making sure that all the different tradesmen and machinery do their job the right way, in the right sequence, while also maintaining the flexibility to adjust for unexpected difficulties and changes.

Yet builders clearly succeed. They safely put up millions of buildings all over the globe. And they do so despite the fact that construction work has grown infinitely more complex over the decades. Moreover, they do it with a frontline workforce that regards each particular job—from pile-driving to wiring intensive care units—much the way doctors, teachers, and other professionals regard their jobs: as specialized domains in which others should not interfere.

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I paid a visit to Joe Salvia, the structural engineer for our new hospital wing. I told him I wanted to find out how work is done in his profession. It turned out I'd come to the right person. His firm, McNamara/Salvia, has provided the structural engineering for most of the major hospital buildings in Boston since the late 1960s, and for a considerable percentage of the hotels, office towers, and condominiums as well. It did the structural rebuilding of Fenway Park, the Boston Red Sox baseball team's thirty-six-thousand-seat stadium, including the Green Monster, its iconic thirty-seven-foot, home-run-stealing left field wall. And the firm's particular specialty has been designing and engineering large, complicated, often high-rise structures all over the country.

Salvia's tallest skyscraper is an eighty-story tower going up in Miami. In Providence, Rhode Island, his firm built a shopping mall that required one of the largest steel mill orders placed on the East Coast (more than twenty-four thousand tons); it is also involved in perhaps the biggest commercial project in the world—the Meadowlands Xanadu entertainment and sports complex in East Rutherford, New Jersey, which will house a stadium for the New York Giants and New York Jets football teams, a three-thousand-seat music theater, the country's largest movie multiplex, and the SnowPark, the nation's first indoor ski resort. For most of the past several years, McNamara/Salvia's engineers have worked on fifty to sixty projects annually, an average of one new building a week. And they have never had a building come even close to collapsing.

So I asked Salvia at his office in downtown Boston how he has ensured that the buildings he works on are designed and constructed right. Joe Salvia is sixty-one, with almost no hair, a strong Boston accent, and a cheery, take-your-time, how-about-some-coffee manner that I didn't expect from an engineer. He told me about the first project he ever designed—a roof for a small shopping plaza.

He was just out of college, a twenty-three-year-old kid from East Cambridge, which is not exactly where the Harvard professors live. His father was a maintenance man and his mother worked in a meat processing plant, but he was good in school and became the first member of his family to go to college. He went to Tufts University planning to become a doctor. Then he hit organic chemistry class.

“They said, ‘Here, we want you to memorize these formulas,’” he explained. “I said, ‘Why do I have to memorize them if I know where the book is?’ They said, ‘You want to be a doctor? That’s what you have to do in medicine—you have to memorize everything.’ That seemed ridiculous to me. Plus I wasn’t good at memorizing. So I quit.”

But Salvia was good at solving complex problems—he tried to explain how he solves quadratic equations in his head, though all I managed to pick up was that I’d never before heard someone say “quadratic equation” in a Boston accent. “I also liked the concept of creating,” he said. As a result, he switched to engineering, a scientific but practical field, and he loved it. He learned, as he put it, “basic statics and dynamics—you know, F equals ma,” and he learned about the chemistry and physics of steel, concretes, and soil.

But he’d built nothing when he graduated with his bachelor’s degree and joined Sumner Shane, an architectural engineering firm that specialized in structural engineering for shopping centers. One of its projects was a new shopping mall in Texas, and Salvia was assigned the roof system. He found he actually understood a lot about how to build a solid roof from his textbooks and from the requirements detailed in building codes.

“I knew from college how to design with structural steel—how to use beams and columns,” he said. And the local building codes spelled out what was required for steel strength, soil composition, snow-bearing capacity, wind-pressure resistance, and earthquake tolerance. All he had to do was factor these elements into the business deal, which specified the size of the building, the number of floors, the store locations, the loading docks. As we talked he was already drawing the contours for me on a piece of paper. It started out as a simple rectangle. Then he sketched in the store walls, doorways, walking space. The design began taking form.

“You draw a grid of likely locations to carry the roof weight,” he said, and he put in little crosses where columns could be placed. “The rest is algebra,” he said. “You solve for X.” You calculate the weight of the roof from its size and thickness, and then, given columns placed every thirty feet, say, you calculate the diameter and strength of the column required. You check your math to make sure you've met all the requirements.

All this he had learned in college. But, he discovered, there was more—much more—that they hadn't taught him in school.

"You know the geometric theory of what is best, but not the practical theory of what can be done," he said. There was the matter of cost, for example, about which he had not a clue. The size and type of materials he put in changed the cost of the project, it turned out. There was also the matter of aesthetics, the desires of a client who didn't want a column standing in the middle of a floor, for instance, or blocking a particular sightline.

"If engineers were in charge, every building would be a rectangular box," Salvia said. Instead, every building is new and individual in ways both small and large—they are complex—and as a result there is often no textbook formula for the problems that come up. Later, for example, when he established his own firm, he and his team did the structural engineering for Boston's International Place, a landmark forty-six-story steel and glass tower designed by the architect Philip Johnson. The building was unusual, a cylinder smashed against a rectangle, a form that hadn't been tried in a skyscraper before. From a structural engineering point of view, Salvia explained, cylinders are problematic. A square provides 60 percent more stiffness than a circle, and in wind or an earthquake a building needs to be able to resist the tendency to twist or bend. But a distorted cylinder it was, and he and his team had to invent the engineering to realize Johnson's aesthetic vision.

Salvia's first mall roof may have been a simpler proposition, but it seemed to him at the time to have no end of difficulties. Besides the concerns of costs and aesthetics, he also needed to deal with the requirements of all the other professionals involved. There were the plumbing engineers, the electrical engineers, the mechanical engineers—every one of them wanting to put pipes, wiring, HVAC units just where his support columns were supposed to go.

"A building is like a body," he said. It has a skin. It has a skeleton. It has a vascular system—the plumbing. It has a breathing system—the ventilation. It has a nervous system—the wiring. All together, he explained, projects today involve some sixteen different trades. He pulled out the construction plans for a four-hundred-foot-tall skyscraper he was currently building and flipped to the table of contents to show me. Each trade had contributed its own separate section. There were sections for conveying systems (elevators and escalators), mechanical systems (heating, ventilation, plumbing, air conditioning, fire protection), masonry, concrete structures, metal structures, electrical systems, doors and windows, thermal and moisture systems (including waterproofing and insulation), rough and finish carpentry, site work (including excavation, waste and storm water collection, and walkways)—everything right down to the carpeting, painting, landscaping, and rodent control.

All the separate contributions had to be included. Yet they also had to fit together somehow so as to make sense as a whole. And then they had to be executed precisely and in coordination. On the face of it, the complexities seemed overwhelming. To manage them, Salvia said, the entire industry was forced to evolve.

For most of modern history, he explained, going back to medieval times, the dominant way people put up buildings was by going out and hiring Master Builders who designed them, engineered them, and oversaw construction from start to finish, portico to plumbing. Master Builders built Notre Dame, St. Peter's Basilica, and the United States Capitol building. But by the middle of the twentieth century the Master Builders were dead and gone. The variety and sophistication of advancements in every stage of the construction process had overwhelmed the abilities of any individual to master them.

In the first division of labor, architectural and engineering design split off from construction. Then, piece by piece, each component became further specialized and split off, until there were architects on one side, often with their own areas of subspecialty, and engineers on another, with their various kinds of expertise; the builders, too, fragmented into their own multiple divisions, ranging from tower crane contractors to finish carpenters. The field looked, in other words, a lot like medicine, with all its specialists and superspecialists.

Yet we in medicine continue to exist in a system created in the Master Builder era—a system in which a lone Master Physician with a prescription pad, an operating room, and a few people to follow his lead plans and executes the entirety of care for a patient, from diagnosis through treatment. We've been slow to adapt to the reality that, for example, a third of patients have at least ten specialist physicians actively involved in their care by their last year of life, and probably a score more personnel, ranging from nurse practitioners and physician assistants to pharmacists and home medical aides. And the evidence of how slow we've been to adapt is the extraordinarily high rate at which care for patients is duplicated or flawed or completely uncoordinated.

In the construction business, Salvia explained, such failure is not an option. No matter how complex the problems he faced in designing that first shopping mall roof, he very quickly understood that he had no margin for error. Perhaps it's the large number of people who would die if his roof collapsed under the weight of snow. Or perhaps it's the huge amount of money that would be lost in the inevitable lawsuits. But, whatever the reason, architects, engineers, and builders were forced long ago—going back to the early part of the last century—to confront the fact that the Master Builder model no longer worked. So they abandoned it. They found a different way to make sure they get things right.

* * *

To show me what they do, Salvia had me come to see one of the construction sites where he and his team were working. His firm happened to have a job under way a short, sunny walk from his office. The Russia Wharf building was going to be a sprawling thirty-two-story, 700,000-square-foot office and apartment complex. Its footprint alone was two acres.

The artistic renderings were spectacular. Russia Wharf was where merchant ships sailing between St. Petersburg and Boston with iron, hemp, and canvas for the shipbuilding industry once docked. The Boston Tea Party took place next door. The new glass and steel building was going up right along this waterfront, with a ten-story atrium underneath and the 110-year-old brick facades of the original Classical Revival structures preserved as part of the new building.

When I arrived for the tour, Salvia took one look at my blue Brooks Brothers blazer and black penny loafers and let out a low chuckle.

"One thing you learn going to construction sites is you have to have the right shoes," he said.

The insides of the old buildings had long been gutted and the steel skeleton of the new tower had been built almost halfway up, to the fourteenth floor. A tower crane hung four stories above the structure. Ants on the ground, we worked our way around a pair of concrete mixing trucks, the cops stopping traffic, and a few puddles of gray mud to enter the first-floor field office of John Moriarty and Associates, the general contractor for the project. It was nothing like the movie construction-site field trailers I had in my mind—no rusting coffee urn, no cheap staticky radio playing, no cigar-chewing boss barking orders. Instead, there were half a dozen offices where men and women, many in work boots, jeans, and yellow safety reflector vests, sat staring into computer terminals or were gathered around a conference table with a PowerPoint slide up on a screen.

I was given a blue hard hat and an insurance release to sign and introduced to Finn O'Sullivan, a smiling six-foot-three Irishman with a lilting brogue who served as the "project executive" for the building—they don't call them field bosses anymore, I was told. O'Sullivan said that on any given day he has between two and five hundred workers on-site, including people from any of sixty subcontractors. The volume of knowledge and degree of complexity he had to manage, it struck me, were as monstrous as anything I had encountered in medicine. He tried to explain how he and his colleagues made sure that all those people were doing their work correctly, that the building would come together properly, despite the enormous number of considerations—and despite the fact that he could not possibly understand the particulars of most of the tasks involved. But I didn't really get his explanation until he brought me to the main conference room. There, on the walls around a big white oval table, hung sheets of butcher-block-size printouts of what were, to my surprise, checklists.

Along the right wall as we walked in was, O'Sullivan explained, the construction schedule. As I peered in close, I saw a line-by-line, day-by-day listing of every building task that needed to be accomplished, in what order, and when—the fifteenth-floor concrete pour on the thirteenth of the month, a steel delivery on the fourteenth, and so on. The schedule spread over multiple sheets. There was special color coding, with red items highlighting critical steps that had to be done before other steps could proceed. As each task was accomplished, a job supervisor reported to O'Sullivan, who then put a check mark in his computer scheduling program. He posted a new printout showing the next phase of work each week, sometimes more frequently if things were moving along. The construction schedule was essentially one long checklist.

Since every building is a new creature with its own particularities, every building checklist is new, too. It is drawn up by a group of people representing each of the sixteen trades, including, in this case, someone from Salvia's firm making sure the structural engineering steps were incorporated as they should be. Then the whole checklist is sent to the subcontractors and other independent experts so they can double-check that everything is correct, that nothing has been missed.

What results is remarkable: a succession of day-by-day checks that guide how the building is constructed and ensure that the knowledge of hundreds, perhaps thousands, is put to use in the right place at the right time in the right way.

The construction schedule for the Russia Wharf project was designed to build the complex up in layers, and I could actually see those layers when Bernie Rouillard, Salvia's lead structural engineer for the project, took me on a tour. I should mention here that I am not too fond of heights. But I put on my hard hat and followed Rouillard—past the signs that said WARNING: CONSTRUCTION PERSONNEL ONLY, around a rusting nest of discarded rebar, over a trail of wood planks that served as a walkway into the building, and then into an orange cage elevator that rattled its way up the side of the skeleton to the fourteenth floor. We stepped out onto a vast, bare, gray slab floor with no walls, just twelve-foot vertical steel columns ringing the outside, a massive rectangular concrete core in the center, and the teeming city surrounding us.

"You can see everything from here," Rouillard said, beckoning me to join him out on the edge. I crept to within three feet and tried not to dwell on the wind whipping through us or the vertiginous distance to the ground as he good-naturedly pointed out the sites along the waterfront below. I did better when we turned our backs to the city and he showed me the bare metal trusses that had been put into the ceiling to support the floor being built above.

Next, he said, will come the fireproofers.

"You have to fireproof metal?" I asked.

Oh yes, he said. In a fire, the metal can plasticize—lose its stiffness and bend like spaghetti. This was why the World Trade Center buildings collapsed, he said. He walked me down a stairway to the floor below us. Here, I could see, the fireproofing material had been sprayed on, a gypsum-based substance that made the ceiling trusses look gray and woolly.

We went down a couple more floors and he showed me that the "skin" of the building had now been hung at those levels. The tall, shiny glass and steel exterior had been bolted into the concrete floors every few feet. The farther down we went, the more the layers had advanced. One team of subcontractors had put up walls inside the skin. The pipefitters had then put in water and drainage pipes. The tin knockers followed and installed the ventilation ducts. By the time we got down to the lowest floors, the masonry, electrical wiring, plumbing, and even some fixtures like staircase railings were all in place. The whole intricate process was astounding to behold.

* * *

On the upper floors, however, I couldn't help but notice something that didn't look right, even to my untrained eyes. There had been rain recently and on each of the open floors large amounts of water had pooled in the same place—up against the walls of the inner concrete core. It was as if the floor were tilted inward, like a bowl. I asked Rouillard about this.

"Yeah, the owners saw that and they weren't too happy," he said. He explained what he thinks had happened. The immense weight of the concrete core combined with the particular makeup of the soil underneath had probably caused the core to settle sooner than anticipated. Meanwhile, the outer steel frame had not yet been loaded with weight—there were still eighteen stories to be built upon it—and that's why he believes the floor had begun to tip inward. Once the steel frame was loaded, he fully expected the floor to level out.

The fascinating thing to me wasn't his explanation. I had no idea what to make of his answer. But here was a situation that hadn't been anticipated on the construction checklist: the tilting of the upper floors. At a minimum, a water cleanup would be needed and the schedule adjusted for it. That alone could throw the builders' tidy plans off track. Furthermore, the people involved had to somehow determine whether the tilting indicated a serious construction defect. I was curious to know how they handled this question, for there was inevitable uncertainty. How could they know that the problem was just ordinary settling, that loading the steel frame would in fact level out the floor? As Rouillard acknowledged, "variances can occur." This was a situation of true complexity.

Back down in the field office, I asked Finn O'Sullivan how he and his team dealt with such a circumstance. After all, skyscraper builders must run into thousands like it—difficulties they could never have predicted or addressed in a checklist designed in advance. The medical way of dealing with such problems—with the inevitable nuances of an individual patient case—is to leave them to the expert's individual judgment. You give the specialist autonomy. In this instance, Rouillard was the specialist. Had the building site been a hospital ward, his personal judgment would hold sway.

This approach has a flaw, however, O'Sullivan pointed out. Like a patient, a building involves multiple specialists—the sixteen trades. In the absence of a true Master Builder—a supreme, all-knowing expert with command of all existing knowledge—autonomy is a disaster. It produces only a cacophony of incompatible decisions and overlooked errors. You get a building that doesn't stand up straight. This sounded to me like medicine at its worst.

So what do you do? I asked.

That was when O'Sullivan showed me a different piece of paper hanging in his conference room. Pinned to the left-hand wall opposite the construction schedule was another butcher-block-size sheet almost identical in form, except this one, O'Sullivan said, was called a "submittal schedule." It was also a checklist, but it didn't specify construction tasks; it specified *communication* tasks. For the way the project managers dealt with the unexpected and the uncertain was by making sure the experts spoke to one another—on X date regarding Y process. The experts could make their individual judgments, but they had to do so as part of a team that took one another's concerns into account, discussed unplanned developments, and agreed on the way forward. While no one could anticipate all the problems, they could foresee where and when they might occur. The checklist therefore detailed who had to talk to whom, by which date, and about what aspect of construction—who had to share (or "submit") particular kinds of information before the next steps could proceed.

The submittal schedule specified, for instance, that by the end of the month the contractors, installers, and elevator engineers had to review the condition of the elevator cars traveling up to the tenth floor. The elevator cars were factory constructed and tested. They were installed by experts. But it was not assumed that they would work perfectly. Quite the opposite. The assumption was that anything could go wrong, anything could get missed. What? Who knows? That's the nature of complexity. But it was also assumed that, if you got the right people together and had them take a moment to talk things over as a team rather than as individuals, serious problems could be identified and averted.

So the submittal schedule made them talk. The contractors had to talk with the installers and elevator engineers by the thirty-first. They had to talk about fire protection with the fireproofers by the twenty-fifth. And two weeks earlier, they had been required to talk about the condition of the core wall and flooring on the upper floors, where the water had pooled, with the structural engineers, a consultant, and the owners.

I saw that the box had been checked. The task was done. I asked Rouillard how the discussion had gone.

Very well, he said. Everyone met and reviewed the possibilities. The owners and the contractors were persuaded that it was reasonable to expect the floor to level out. Cleanup was arranged, the schedule was adjusted, and everyone signed off.

* * *

In the face of the unknown—the always nagging uncertainty about whether, under complex circumstances, things will really be okay—the builders trusted in the power of communication. They didn't believe in the wisdom of the single individual, of even an experienced engineer. They believed in the wisdom of the group, the wisdom of making sure that multiple pairs of eyes were on a problem and then letting the watchers decide what to do.

Man is fallible, but maybe men are less so.

In a back room of the field office, Ryan Walsh, a buzz-cut young man of about thirty wearing a yellow reflector vest, sat in front of two big flat-screen displays. His job, he explained, was to take all the construction plans submitted by each of the major trades and merge them into a three-dimensional floor-by-floor computer rendering of the building. He showed me what the top floor looked like on the screen. He'd so far loaded in the specifications from nine of the trades—the structural specs, the elevator specs, the plumbing specs, and so on. He used his mouse to walk us through the building as if we were taking a stroll down the corridors. You could see the walls, the doors, the safety valves, everything. More to the point, you could see problems—a place where there wasn't enough overhead clearance for an average-size person, for example. He showed me an application called Clash Detective that ferreted out every instance in which the different specs conflicted with one another or with building regulations.

"If a structural beam is going where a lighting fixture is supposed to hang, the Clash Detective turns that beam a different color on-screen," he said. "You can turn up hundreds of clashes. I once found two thousand." But it's not enough to show the clash on the screen, he explained. You have to resolve it, and to do that you have to make sure the critical people talk. So the computer also flags the issue for the submittal schedule printout and sends an e-mail to each of the parties who have to resolve it.

There's yet another program, called ProjectCenter, that allows anyone who has found a problem—even a frontline worker—to e-mail all the relevant parties, track progress, and make sure a check is added to the schedule to confirm that everyone has talked and resolved the matter. When we were back at the McNamara/Salvia offices, Bernie Rouillard showed me one such e-mail he'd gotten that week. A worker had attached a digital photo of a twelve-foot steel I beam he was bolting in. It hadn't lined up properly and only two of the four bolts could fit. Was that all right, the worker wanted to know? No, Rouillard wrote back. They worked out a solution together: to weld the beam into place. The e-mail was also automatically sent to the main contractor and anyone else who might potentially be required to sign off. Each party was given three days to confirm that the proposed solution was okay. And everyone needed to confirm they'd communicated, since the time taken for even this small fix could change the entire sequence in which other things needed to be done.

Joe Salvia had earlier told me that the major advance in the science of construction over the last few decades has been the perfection of tracking and communication. But only now did I understand what he meant.

* * *

The building world's willingness to apply its strategies to difficulties of any size and seriousness is striking. Salvia's partner, Robert McNamara, for instance, was one of the structural engineers for the Citicorp (now Citigroup) building in midtown Manhattan, with its iconic slanted rooftop. It was planned to rise more than nine hundred feet on four nine-story-tall stiltlike columns placed not at the building's corners but at the center of each side and steadied by giant, hidden chevron-shaped braces designed by William LeMessurier, the project's lead structural engineer. The visual effect was arresting. The colossal structure would look like it was almost floating above Fifty-third Street. But wind-tunnel testing of a model revealed that the skyscraper stood so high above the surrounding buildings in midtown that it was subject to wind streams and turbulence with forces familiar only to airplane designers, not to structural engineers. The acceptable amount of sway for the building was unknown.

So what did they do? They did not scrap the building or shrink it to a less ambitious size. Instead, McNamara proposed a novel solution called a "tuned mass damper." They could, he suggested, suspend an immense four-hundred-ton concrete block from huge springs in the building's crown on the fifty-ninth floor, so that when wind pitched the building one way, the block would swing the other way and steady it.

The solution was brilliant and elegant. The engineers did some wind-tunnel testing with a small model of the design, and the results were highly reassuring. Nonetheless, some chance of error and unpredictability always remains in projects of this complexity. So the builders reduced their margin of error the best way they knew how—by taking a final moment to make sure that everyone talked it through as a group. The building owner met with the architect, someone from the city buildings department, the structural engineers, and others. They reviewed the idea and all the calculations behind it. They confirmed that every concern they could think of had been addressed. Then they signed off on the plan, and the skyscraper was built.

It is unnerving to think that we allow buildings this difficult to design and construct to go up in the midst of our major cities, with thousands of people inside and tens of thousands more living and working nearby. Doing so seems risky and unwise. But we allow it based on trust in the ability of the experts to manage the complexities. They in turn know better than to rely on their individual abilities to get everything right. They trust instead in one set of checklists to make sure that simple steps are not missed or skipped and in another set to make sure that everyone talks through and resolves all the hard and unexpected problems.

"The biggest cause of serious error in this business is a failure of communication," O'Sullivan told me.

In the Citicorp building, for example, the calculations behind the designs for stabilizing the building assumed the joints in those giant braces at the base of the building would be welded. Joint welding, however, is labor intensive and therefore expensive. Bethlehem Steel, which took the contract to erect the tower, proposed switching to bolted joints, which are not as strong. They calculated that the bolts would do the job. But, as a *New Yorker* story later uncovered, their calculations were somehow not reviewed with LeMessurier. That checkpoint was bypassed.

It is not certain that a review would have led him to recognize a problem at the time. But in 1978, a year after the building opened, LeMessurier, prompted by a question from a Princeton engineering student, discovered the change. And he found it had produced a fatal flaw: the building would not be able to withstand seventy-mile-an-hour winds—which, according to weather tables, would occur at least once every fifty-five years in New York City. In that circumstance, the joints would fail and the building would collapse, starting on the thirtieth floor. By now, the tower was fully occupied. LeMessurier broke the news to the owners and to city officials. And that summer, as Hurricane Ella made its way toward the city, an emergency crew worked at night under veil of secrecy to weld two-inch-thick steel plates around the two hundred critical bolts, and the building was secured. The Citicorp tower has stood solidly ever since.

The construction industry's checklist process has clearly not been foolproof at catching problems. Nonetheless, its record of success has been astonishing. In the United States, we have nearly five million commercial buildings, almost one hundred million low-rise homes, and eight million or so high-rise residences. We add somewhere around seventy thousand new commercial buildings and one million new homes each year. But "building failure"—defined as a partial or full collapse of a functioning structure—is exceedingly rare, especially for skyscrapers. According to a 2003 Ohio State University study, the United States experiences an average of just twenty serious "building failures" per year. That's an annual avoidable failure rate of less than 0.00002 percent. And, as Joe Salvia explained to me, although buildings are now more complex and sophisticated than ever in history, with higher standards expected for everything from earthquake proofing to energy efficiency, they take a third less time to build than they did when he started his career.

The checklists work.