Converging on the Barrier

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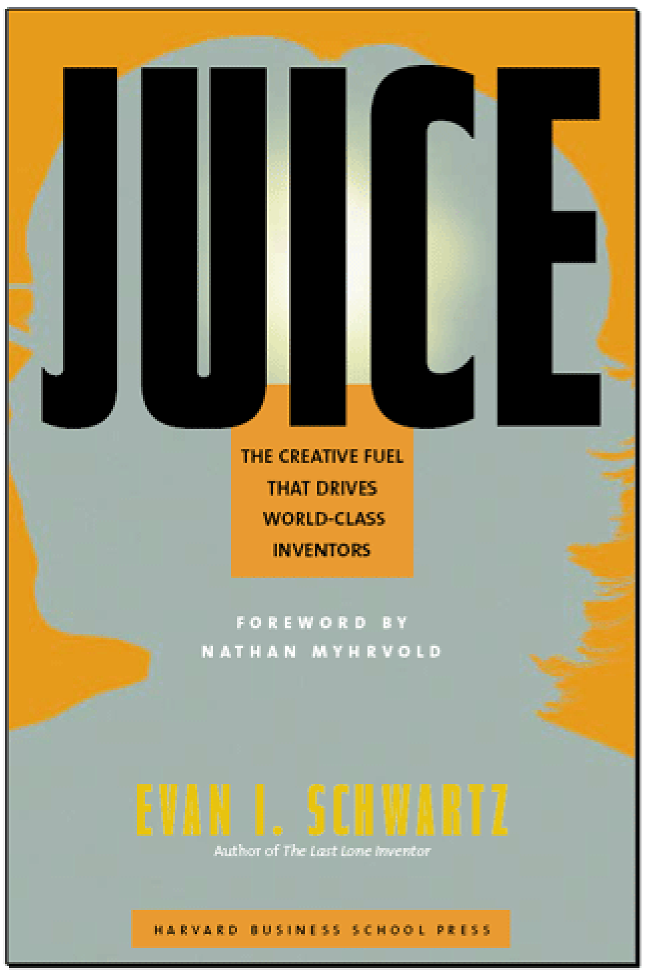

Within established industries, lots of inventors often converge on the same barrier at roughly the same time, and it takes a little extra juice to be the individual or team to be the first to break through. Carl Crawford has got it. He was one of a handful of inventors to discover a critical boundary at the core of the medical equipment business, and he is constantly searching for new ones. Crawford is slightly built with thinning light brown hair, and he acknowledges that he's "somewhat weird, like most inventors I know." A bicycle enthusiast who likes to get up early to go for a ride every morning, he sometimes becomes so preoccupied with technical problems in his mind that he forgets where he is or how he got there. Growing up in Milwaukee in the 1960s, Crawford recalls spending hours ripping apart and repairing transistor radios. He also remembers his family's shock upon getting his SAT results: a 200 on the verbal portion, the lowest possible score, and a near perfect 790 on the math portion. "I couldn't communicate," he says. That has since changed, but Crawford still points to these scores as evidence of his quirkiness and his reliance on having his inventions speak for him.

While Crawford was studying electrical engineering at Purdue, a professor interested Crawford in computed tomography, or CT. At first, Crawford says, "I couldn't spell CT." Not long after receiving his Ph.D. from the same institution, he took a job in his hometown of Milwaukee as a staff engineer with GE Medical Systems. At GE, he was struck by the limitations of commercial CT scanners (some times called CAT, or computer-assisted tomographay, scanners). The technology was already a mainstay of the conglomerate's medical equipment business. A vast improvement over the film-based X-ray machine, which took only a two-dimensional snapshot, CT provided superlative three-dimensional images of the body's interiors. If something important, such as a tumor, was blocked by bones or other organs, the X-ray machine would often miss it. With CT, though, doctors could finally see everything in graphic detail.

The technology had revolutionized medical diagnostics to such an extent that its inventor, Allan Cormack, and the engineer who commercialized it, Godfrey Houndsfield, shared the Nobel Prize in medicine in 1979. By then, these SUV-sized machines had been installed in hospitals all over the developed world, at a cost of about $1 million each. A patient, lying on a conveyor, was carried through the contraption much as a piece of paper is fed through a fax machine, except that the scanning occurred in three dimensions. The scanner acquired cross-sectional images of the head and body and then re-assembled the slices and rendered them as images for study by doctors. Indeed, the Latin root *tomo* means "slices." Typically the slices would be only ten millimeters thick, so the machine had to acquire hundreds of them.

But these machines had a drawback: It often took several minutes to scan an entire body. Each thin slice had to be rendered as perfectly as possible. The slightest movement by the patient, including something as simple as breathing, would cause blurring or streaking in the images. As a patient moved through the scanner, technicians had to pause each time the scanner arrived at a new section of the body. To get a proper scan, patients had to hold their breaths during each scan to prevent artifacts and gaps. "How long can a person hold their breath?" remarks Crawford. "For twenty seconds, maybe thirty or forty, if you're really healthy." Between scans, the patient was typically allowed to breathe for only six to eight seconds.

Inventors around the world had been working to improve the machines for years, trying to detect barriers and work through them. First-generation scanners were based on a single X-ray detector that rotated and translated around the cross sections. This process often took more than an hour, and it required such stillness from patients that early CT scanning was limited to the head. Later scanners employed an array of detectors. Now each slice could be acquired in several seconds. This improvement opened up new applications for scanning not only the head but also the neck, chest, abdomen, pelvis, legs and feet. But most hospitals had only begun buying these machines when they started to come equipped with hundreds of detectors. This reduced scan time even further per body section, but the problem remained of patients having to hold their breaths, notes Crawford, and many of the images still ended up with some blurring and had to be redone.

After joining GE, Crawford spent large chunks of time reviewing the technical literature, a habit he continues to this day. To detect a new barrier, and therefore a new opportunity, he searches for flaws. They often present themselves as holes in logic. "I look for assumptions that might be wrong," he says. "I also look for adjectives and adverbs. They often hide the fact that the writers don't understand fully what they are writing about." In articles about CT scanners, he found an interesting logic gap. Previous inventors had believed that the solution was to incorporate increasing numbers of X-ray detectors into these machines or to rotate them faster around the body.

Crawford, however, hit up against a different obstacle. "History said the patient had to be completely stationary," he says. "That was impractical." He believed that the ultimate CT scanner should scan sections of the body in less than one second. In this way, the patient wouldn't have to worry at all about blurring due to moving or breathing.

Others hadn't seen it that way. Back in the mid-1980s, the barrier to instantaneous scanning was thought to be the time it took for the X-ray tubes to cool or by limitations on data bandwidth. "We made the assumption that data acquisition was not limited by those factors," he says.

Crawford and a fellow engineer named Kevin King were especially focused on the problem. Like the Wright Brothers, Crawford and King were not far apart in age, and they developed an effective way of working together. When one got burned out thinking about something for too long, the other would pick up where the first one left off. By bouncing ideas off of each other, they discovered a previously unseen opportunity: Why not find a way to acquire the image data continuously, rather than in discrete slices and intervals? Why not find a way to scan sections of the body in a single breath hold so that blurring is no longer and issue? Why not reduce the time between scans to zero? These were radical questions at the time. "We had to cross this threshold," Crawford says. In heading down this new path, Crawford and King reinvented the challenge. They set out to create a new machine that would scan the body in a new way.

To solve the problem, they homed in on the scanning pattern itself. If the patient was moving, they thought, the X-ray detectors would no longer be able to capture a perfectly cut slice of the body. Instead, it would be like winding a string around a slowly moving cylinder. The detectors would actually be acquiring a continuous spiral pattern. The scanning patter would resemble a Slinky toy rather than slices of salami. Along with the new pattern, there needed to be a new mathematics for translating data taken from a moving patient in this way.

The two engineers had detected the roadblock, but they didn't yet know how they were going to get around it. "That was the barrier," Crawford says. "We created our own necessity just by looking at the problem in a different way." They were determined to come up with a new method of scanning and not a better way to conduct the old method. They viewed the existing scan pattern, fixed for the preceding twenty years, as obsolete.

Hitting The Next Barrier

In an internal GE paper in 1987, Crawford and King first described their resulting solution, based on a breakthrough interpolation algorithm. They called their invention "helical extrapolative scanning." Also known as spiral CT scanning, the technology was first introduced to the industry in 1989 and then perfected in the early 1990s, when it would lead to what Stanford University radiologist Sandy Napel called a "virtual renaissance in CT, improving its capabilities in existing applications and creating new ones." By the mid 1990s, virtually all CT scanners would be spiral scanners.

But Crawford and King weren't the only ones who detected the same barrier. As is typically the case, they were simply *among* the least the Wrights had a few years had a few years to work through their barrier before others caught up with them.

Crawford and King had no time at all. Other inventors and corporate researchers were on the road toward a similar result. In their patent search, conducted along with GE attorneys, they came across a 1989 University of Illinois patent by inventors headed down a convergent path. They also discovered a 1986 patent, filed in the United States by a Toshiba engineer, that referred to helical scanning. But the biggest source of competition came just as Crawford and King were getting ready to file their own patent applications and as they were preparing for submission in the journal of *Medical Physics*.

In June 1989, Crawford went to Berlin to attend an industry conference. It was there that he met his counterpart at the medical systems division of Siemens, the German industrial giant. Electrical engineer Willi Kalender was part of a Siemens team readying its own patent applications, as well as a paper on spiral CT scanning, for the journal *Thoracic Radiology*. The two groups knew of each other but didn't know exactly what the other was working on. One late night, Crawford and Kalender met and went out for a drink. The most convenient bar happened to be located in a nearby brothel. It was there, over beers in that less than reputable establishment, that Crawford said something like, "I am working on the best thing, something that will revolutionize CT, but I can't tell you what it is." Hearing that, Kalender replied with something like, "So am I!" They sidestepped their secrets for the rest of the evening, beer after beer, trying to talk about other things.

In the subsequent months both teams filed for patents and submitted papers. By the end of 1990, the patents and papers of both teams had been published, and their work was no longer secret. At that year's radiology conference in Chicago, each team summarized its work and discussed the results back to back, in the same room, on a Sunday morning. First Kalender, from the Siemens team, spoke about spiral scanning. King from the GE team, followed with his presentation on helical scanning, a minor difference in terminology that continues to be argued about.

With both teams detecting the same barrier and announcing similar breakthroughs, one might think that the race to the market would have been intense, but that wasn't the case. Instead of supporting the findings of their own engineers, the management of GE Medical Systems went on the attack against this new method of scanning. GE denounced the approach taken by Crawford and King. "GE was scared about cannibalizing" its existing market, Crawford recalls. At that time the world leader in selling the current million-dollar machines, the GE division was lead by managers and marketing executives who figured that word of a revolutionary new approach could kill their current pipeline of product sales, significantly impacting near-term revenue. They assigned other GE executives to write papers claiming that this new form of CT scanning wouldn't work, according to Crawford.

Siemens took the opposite approach, rushing a new-generation product to market early in 1991. The Siemens product started capturing some market share, at the expense of GE. But according to Crawford, Siemens had released its machine prematurely because it incorporated the wrong algorithm for interpolating the spiral scan data. Kalender seemed to encounter a significant new barrier. The Siemens engineer was unable to correct for a mathematical effect of the spiral scanning process, and this led to a doubling of the scan time. That defect slowed Siemens from further penetrating the market, as Kalender and his team tried to figure out how to overcome this more specific problem.

Crawford and King, meanwhile, hit this new barrier hard. What was this more specific barrier? As it turns out, helical scanning until then was based on collecting data in half-scans of approximately 180 degrees. One set of X-ray detectors scanned the top half of the body, and a second set scanned the bottom half. With the spiral scan pattern, the body moved too fast to get this approach to work without producing image artifacts. Crawford and King, in a separate patent filed only two weeks after their first one, disclosed something new: a method of having all the X-ray detectors acquire data in full, 360-degree scans around the body, thereby obtaining *two* measurements of everything. The double measurements were used to cancel out the image artifacts and retain the time goals. "Our invention was in doing it without doubling the scan time," Crawford says.

This was the breakthrough that eventually caused a massive changeover in a rich market. Within two years, the results from these new spiral scanners were proven to be so superior that everyone became convinced. Even those within GE protecting the status quo had to acknowledge that the new spiral CT technology was here to stay. Within ten years, everything had been replaced. By now, virtually all the CT scanners in use worldwide are helical, or spiral, scanners. According to the National Electrical Manufacturers Association, some twenty thousand of these machines were sold in the 1990s. At about $1 million each, that's $20 billion in revenues.[14]

The machines opened up new applications, such as virtual colonoscopies, in which a patient's colon seems to become the setting of the latest Pixar movie. Entrepreneurs began buying the machines to circumvent the existing healthcare system, opening CT scanning centers in malls and storefronts, typically charging about $1,000 for a full body scan that can detect tumors as small as three millimeters wide in any organ. A recent study in the *New England Journal of Medicine* showed that CT scanners can now display such precise rendering in detecting colon cancer that they can serve as accurate replacements for invasive and expensive colonoscopy procedures.

As these case studies show, the barrier that is blocking a new invention is often more complex than it may seem at first. Finding the obstruction that is holding back a valuable improvement can set off a backlash inside a corporation or an industry before the new invention ever gets a chance to disrupt the market. As such, detecting barriers can be considered dangerous, even subversive, behavior. Once that obstacle is out of the way, however, inventors can see their way more clearly.

Epilogue: Some of inventors have been genuinely surprised by their creations. Carl Crawford, the coinventor of the spiral CT scanner, left GE Medical Systems in 1995 and became a vice president at Analogic Corporation, a Peabody, Massachusetts, company whose culture focuses on inventing across a half dozen domains. Founded by Bernard Gordon, an illustrious inventor of analog-to-digital signal processing chips, Analogic never posted a loss in its three decades as a public company, but it has also never been known as a high-flying company. In 2000, Gordon received a call from Lockheed Martin about adapting it CT scanners for possible applications in airport baggage scanning. Gordon put Crawford in charge of the project. Not long after 9/11, the government decided to buy there new machines in bulk to scan checked baggage at U.S. airports for the first time. Analogic won a big part of the business, and it delivered hundreds of these machines in December 20002. Sitting in Gordon's corner office only a few days after the *Boston Globe* named Analogic Massachusetts's best-performing company in its annual "Globe 100" survey, Crawford took it in stride. This was pretty much a one-time gain, he said. Gordon agreed: "We probably can't grow profit margins by 10,872 percent every year."

Citations

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