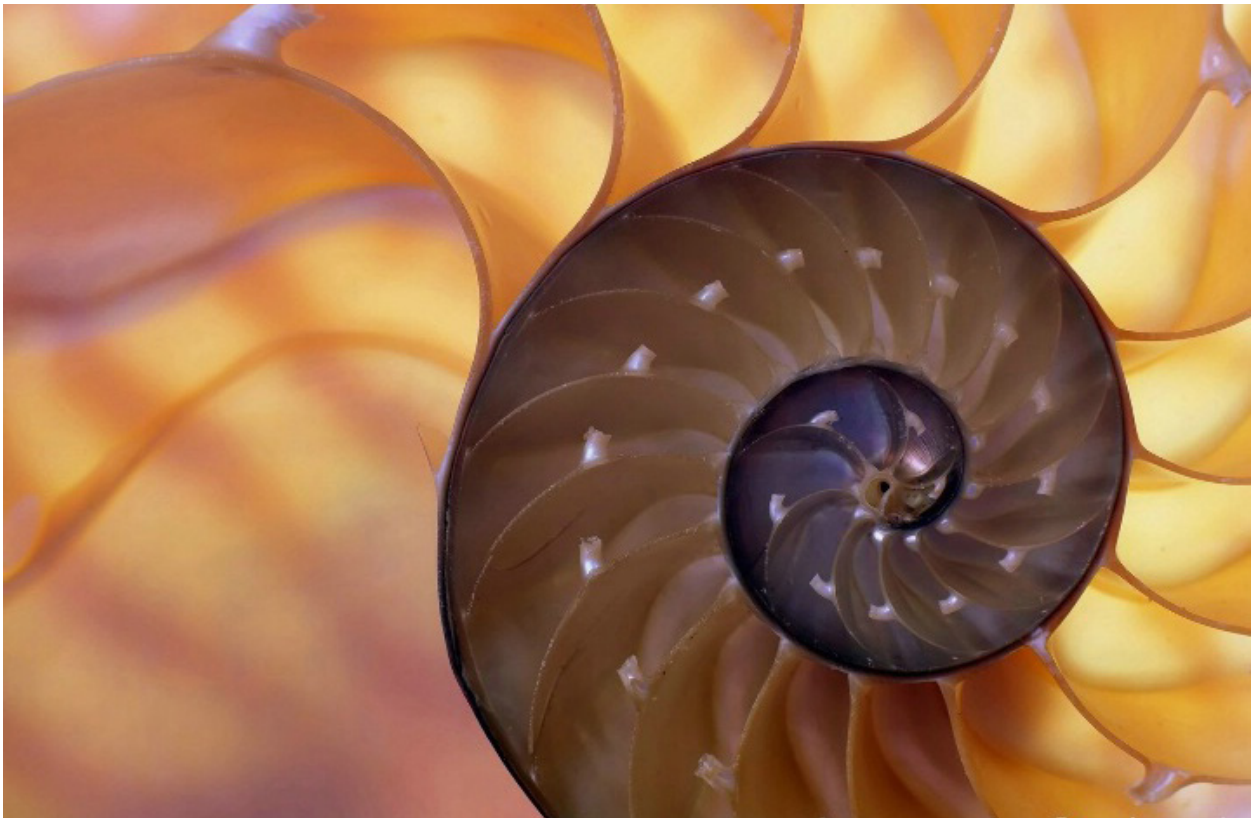
NATURE-INSPIRED INNOVATION: PAX WATER TECHNOLOGIES

PAX and its subsidiaries constitute a novel research and product-engineering firm that is based on sophisticated manipulation of flow inspired by nature. PAX provides fluid and heat technologies for air handling, water and wastewater management, and industrial mixing. PAX also researches surface profile modifications for watercraft. The company has an active interest in water and wastewater management, and this case study will cover the overall inception and structure of PAX and its subsidiary, PAX Water Technologies.

The Company

PAX is the child of career trailblazer Jay Harman. Prior to PAX, his career evolved from being a naturalist for the Australian Department of Fisheries and Wildlife to founding one of Australia's largest technology firms. He has delved into projects that include environmental education, award-winning nautical design, biomedical devices for blood sugar monitoring, and asbestos encapsulation. Uniting these disparate ventures is Harman's profound sense of curiosity, which fuels his innovative thinking.

Harman confesses that, "the only thing in life that interested me with any sort of power [was the preservation of nature]." Throughout his career he saw long-developed preservation projects erased by the swift action of business interests. Harman set out to unite his thirst for innovation with his commitment to environmental preservation by creating a company that could ease environmental problems while also being economically viable. In this way he could preserve the nature he held so dear, while also demonstrating that innovation and success need not lead to destruction of the natural world. "Nature has already solved every problem humans face and have ever faced," Harman says. "If you see nature as our university, you're not going to burn down the university; you're going to protect it."



PAX Scientific has developed air and water propeller technology based on a recurrent form in nature, the centripital spiral, to greatly improve the efficiency of existing fan technology. The mathematical ratio of this pattern, exhibited in this nautilus, is commonly known as the Fibonacci Sequence or the Golden Ratio.

PAX is based on a single wide-reaching biomimetic idea that dramatically improves the efficiency of fans and mixing equipment. Because these improvements are applied to very different products, PAX has created subsidiary companies that target each of these markets separately. The companies within the PAX umbrella include PAX Scientific, PAX Mixer, PAX Fan, and PAX Water. This case study will describe the creation of the overarching PAX technology as well as the business development of one of the subsidiary companies, PAX Water.

Founder Jay Harman noticed as a child that seaweed, among other objects in nature, tended to form the same curviture to allow water to pass. As an adult, he studied the mathematics behind this phenomenon to apply it to PAX's technologies.

A Nature-Inspired Solution

The Problem with Flow

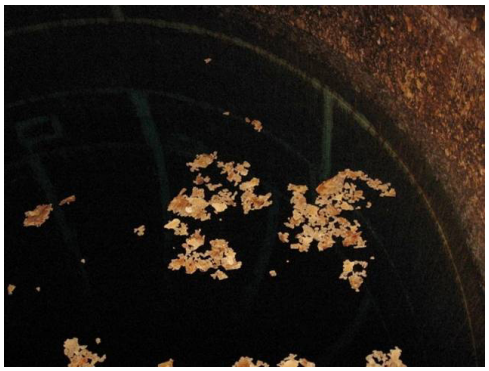
Traditional fans, pumps, and propellers—collectively known as rotational equipment—consist of planar surfaces, or surfaces with simple curvature in only one axis. They use these geometries to generate centrifugal forces—forces moving outward from the center of rotation. These forces then generate turbulence that causes the gas or fluid to move or mix. Rotational equipment design has changed only incrementally since the Egyptians and Archimedes developed their solutions, both over 4,000 years ago. Gradual modification and tinkering have produced modern designs that are not much different from their ancient predecessors. Fundamentally, these technologies remain inefficient. Design faults include drag resistance, low output, energy inefficiency, excessive noise, and component wear and tear.

The PAX Solution

Taking inspiration from nature gave Harman the fresh approach he needed to tackle the problem of moving fluids. As a child in Western Australia he had noticed that, "seaweed is fragile, but it survives storms by changing its shape to let the water go by." Harman noticed a recurrent geometry that has fascinated man throughout the ages. From water flows, to kelp patterns, to shell architectures, nature repeatedly utilizes 3-dimensional centripetal spirals—oriented toward the center of curvature—for liquid flows. Digging deeper, he realized that the most efficient way to move matter and energy seems not to be a straight line, but a curve known as Phi. Phi also goes by several other names: Golden Ratio, Golden Section, Golden Mean, or Fibonacci progression.

With this geometry in mind, Harman relocated to San Rafael, California, and founded PAX Scientific in 1997 to be the vessel for his environmentally positive entrepreneurial ambitions. What he sought to do with PAX was explore and commercialize a consistent pattern from nature, the whirlpool.

Reverse engineering this geometry was an evolving process that began with testing shell interiors as impellers. When the results were promising, Harman and his team moved forward in a more scientific manner using fluid dynamics and computer modeling software. Harman was able to tease out what he calls the "PAX streamlining principle." This principle is based on a scalable geometry of compound curves in multiple axes, resulting in an organic shape derived from the Golden Ratio. When an impeller of this design rotates recessively, it produces centripetal forces. In other words, the fluid at the outer edges of the spiral is pulled toward the center. The result is the reduction or elimination of drag and resistance.



Stagnant water tends to stratify in layers of different temperatures. The topmost layer is warmest, encouraging bacterial growth and nitrification. The bacterial growth in water tank on the right is indicative of under-treated water.

It was the reduced vibration, reduced noise, and more efficient operation that prompted PAX to test its design as an air handling solution. In his first application of this principle to a domestic exhaust fan, Harman created a fan half as noisy, 75% more efficient, with markedly decreased vibration. Further tests demonstrated that the approach could be applied to fluids of all types. Not just rotors, fans, and impellers would benefit. Vehicles move through fluids as well, and would see substantial benefits from application of the PAX Principle. Using these technologies, PAX could lead an approach to address problems with a thematically biomimetic approach to restore natural functionality to engineered systems.

The Problem Applied: Mixing Water

Devising safe and environmentally responsible methods of maintaining drinking water quality has gained increasing momentum in the realm of both American and Canadian legislation. Recent regulations aim to reduce levels of potentially harmful disinfectants and their byproducts, while also ensuring high-quality drinking water. While disinfectants are needed to protect the general public from microbial contamination, they produce harmful byproducts that have been linked to cancer, reproductive complications, and developmental health risks.

The most common reason for poor water quality is a problem with water storage. Stagnation occurs when water is poorly mixed or inadequately circulated, often due to the mismatch between tank size and daily demand. Tanks can be ten or more times larger than daily demand in order to meet future projected demand and fire/emergency capacity. This overcapacity is particularly exaggerated in new developments with incomplete residency, and therefore insufficient daily turnover of stored water. Additionally, thermal loading by sunlight and ambient air results in temperature stratification—the vertical separation of water with varying temperatures. This condition prevents natural mixing, as new, colder water slides under the older, warmer water. Stratification only requires a 0.1 degree Celsius temperature differential. The older, warmer water at the top loses its disinfectant capacity and can experience bacterial and microbial growth.

For years the assumption was that treated water would maintain its quality throughout storage periods with little change. In fact, the water degrades substantially over time when the warm upper layer resulting from stratification loses its chemical disinfectant content, or residual. Following this realization, the potable water industry assumed that their only option was to manage the existing biofilm layer that would continue to degrade this residual, rather than to prevent its formation in the first place. Water utilities often use additional disinfectants to manage the bio-load, or undesirable microbial population. Solutions include elaborate systems for periodically dosing a storage tank with chemicals. Recent regulations have acted to limit the use of disinfectant byproducts, which have rendered this avenue less feasible. At the same time, the utilities are expected to produce water of a higher quality, lower in microbial contaminants such as *Cryptosporidium* and *Giardia*. Many utilities shifted over to chloramine disinfection, which generates fewer disinfectant byproducts, but can cause unfavorable nitrification, a process by which specific bacteria proliferate in the distribution, causing a rapid loss of water quality.

Bacterial loading that surpasses the safety threshold results in unsafe water and public boil water notices. Utilities are then forced to deactivate storage tanks for cleaning at a very high cost to the utility and decreased

The Lily impeller, modeled after the streamlines of a whirlpool, is used to create an axial jet which entrains the entire tank volume into a large ring vortex, similar to a smoke ring. Ring vortices are persistent flow structures due to minimal internal friction.

service for the public. This public relations nightmare leads to an unpleasant period for frequently cash-strapped utilities, and stymies other efforts involving their municipality, such as rate increases or capital investments. Bulk addition of chlorine as a resolution method is another strategy that can also lead to high levels of toxic disinfectant byproducts as the microbial layer degrades. After a certain point, utilities have no choice but to dump their tanks. One utility in California spent $65,000 in one year on water that had to be dumped due to stratification-related degradation, a stunning 15.4 million gallons.

Chemical treatment, aside from being associated with potential safety issues, has been unsuccessful in preventing stratification and stagnation. Another leading remedy has been to periodically pump water between storage tanks in an attempt to mix the stratified layers. Pumping water between storage tanks consumes substantial power and requires additional operator time. While the water is being pumped back and forth, water levels in both tanks are artificially low, hindering the ability to respond to an emergency. Furthermore, this type of pumping is only periodically feasible, and research has shown that chemical and temperature stratification occurs in as little as four hours after pumping ceases.

Competing Mechanical Mixing Systems

In response to increasing pressure from water regulation authorities, utilities have turned to mechanical solutions to solve the underlying problem rather than treat the symptoms. However, performance of both initial passive and active systems was limited, leaving some utilities skeptical of the potential of these technologies.

The most common types of mechanical systems, as well as PAX's most common competitors, are floating draft tube active mixers, and duckbill/flap valve or nozzle-type passive mixers. Floating draft tube active mixers float on the surface of water tanks, drawing water up from the bottom of the tank through an adjustable draft tube suspended from the underside of the floating mixer. Water exits horizontally out of the top of the mixer after passing through an impeller powered by either the electric grid or solar panels. However, these floating draft tube active mixers can work poorly in tanks with fluctuating water levels or layers of ice at the top of the mixer. These systems also require an anchoring to allow for variations in water levels and power cabling through the tank wall or existing hatches. One of PAX's primary competitors uses this model, powered by solar panels mounted to the top of the water storage tank. Various installations have proven that this particular system does not feed the impeller enough energy to properly mix the water in the first place, causing either stratification or ice build-up.

The duckbill/flap valve or nozzle-type passive mixers are even more problematic than most floating systems. These systems contain a valve or nozzle, manufactured from a type of rubber or elastomer, that is installed at the end of the tank inlet pipe. The nozzles maintain a flattened "duck bill" shape until water flows into the tank inlet pipe. At this point, it opens slightly to allow the flow to enter the tank at a high velocity. The resulting jet flow causes the water to rotate in the tank, mixing as it goes. The system is considered passive because no direct mechanism is required at the tank site to mix the water, since the nozzle channels energy from the pumped water. However, passive mixers are often ineffective in high velocity mixing when there is an insufficient flow of water into the tank, and involve hundreds of pounds of additional equipment.

These systems operate best in the early morning, when water tanks refill quickly, but do not operate as well throughout the rest of the day, especially when they are needed most in the afternoon, when temperatures

tend to be highest in hot climates. In very cold climates, the lack of continual mixing leads to ice formation that can damage the expensive equipment in mixing systems.

Water storage technology is clearly in need of innovative solutions. Conventional solutions, including existing systems for mechanically mixing water, are unsatisfactory and often add more problems to the system. New regulations aim to address these issues, furthering the need for innovation by limiting utilities' ability to simply use more disinfectants to manage bacterial growth.

The Lily Impeller improves on conventional impeller technology by reducing drag. The result is that the device requires far less energy to operate than conventional water mixing technologies.

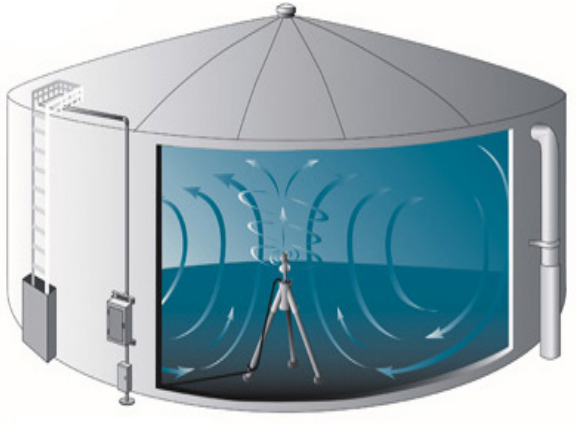
The PAX Water Solution

In 2004, PAX employees identified the new potable water regulations to limit disinfectants and require increased water quality as a major business opportunity. PAX Water Technologies was then founded in 2006 as a subsidiary of PAX Scientific. PAX Water is charged with developing and applying the PAX impeller technology for water and wastewater treatment applications. From 2005-2007, PAX Scientific had focused primarily on technology development, but had not fully realized commercial applications. Though they possessed the Lily Impeller, and the data to show that it offered tremendous improvements over other liquid impellers, PAX Scientific had not yet been successful in bringing this innovation to market. When PAX Water was established in 2006, its primary focus was to identify market opportunities for the Lily Impeller in water applications, to bring PAX Scientific's extensive R&D to industry. Although PAX Water is still a majority owned subsidiary, it has its own facility with its own support staff, and is targeting the potable water market.

PAX employees knew that an effective mechanical solution for stagnation could amplify the sterilizing effect of chemicals already present in the distribution system. The result would be quality water containing the desired amount of disinfectant residual, with reduced chemical addition and disinfectant byproduct. It could also solve stratification without the need for additional chemicals that cause cascading problems.

In order to address the water mixing challenge, the company developed the PAX Water Mixer, a submerged mechanical mixing system. No other mechanical solution had offered a compact, efficient solution to the stratification and stagnation problem. PAX was able to avoid bulky installations by focusing on continuous operation to deliver 24/7 mixing. Installation can be accomplished in a matter of hours, with or without draining the storage tank. The product requires little external training or tank modifications. Initial thermal uniformity is usually re-established within the first 24 hours. Mixing occurs continuously to eliminate stratification, distribute disinfectants uniformly, and prevent nitrification. Within 2-3 weeks biofilms are killed off, and residual chlorine consumption is nearly eliminated. On-site chemical addition can be reduced because the conditions that encourage bacterial growth are prevented from occurring. If necessary, these chemicals can be dispersed throughout the tank rapidly, reducing the volume of chemicals needed. However, many of PAX's installations no longer require additional chemicals once effective circulation is established. Additionally, when the water is in constant motion, biofilms are inhibited from growing on the surfaces inside of the tank. Mixing also minimizes ice formation, which can damage the interior of the tank when large chunks of ice tear the sides of the tank, or drag expensive equipment up and down as they rise and fall with the water levels.

Central to the design is the patented Lily Impeller, which was designed using computational fluid dynamics (CFD) to reverse engineer the creation of whirlpool flows found in nature. The ratio of impeller size to mixed water



The PAX Water Mixer's Lily Impeller is designed using computational fluid dynamics to reverse engineer the creation of whirlpool flows found in nature. The diagram illustrates the movement the impeller creates.

volume capacity is unprecedented. It generates a ring-shaped vortex that efficiently moves water throughout the tank, in a form of "organized turbulence" with an optimal flow regime that reduces friction and ensures complete mixing. The impeller is optimally positioned atop a rubber-footed stand that does not damage the tank interior. It then generates a strong axial fluid jet, establishing an energy efficient and stable flow regime throughout the entire storage tank. To establish the desired toroidal—doughnut shaped—flow, the mixer requires a minimum water depth of roughly 8 feet.

This solution is effective in a variety of tank geometries, even those with internal supports. The mixer can also address standpipes up to 120 feet tall. Moreover, mixing can be powered by a solar power system, the PAX Water Mixer Solar Power unit. PAX Water has demonstrated complete mixing in ground level and elevated water storage facilities.

Installations have successfully mixed reservoirs up to 20 million gallons. A 1/3 horsepower unit installed in reservoirs of up to 7 million gallons uses only the energy of three 100-watt light bulbs, and costs roughly $1.00 per day to power. The cost of a mixer, including installation, taxes, and a two year parts and labor warranty is roughly $35,000 depending on site install characteristics. Motors must currently be replaced every 5 years at $2,000 a piece.

A Kentucky utility chose the PAX Water Mixer as its mechanical mixing system because of its 8 hour installation time, $2000-$8000 installation cost, 500-1200 rotations per minute (RPM), and 65 lb weight. A floating draft tube active mixer and a duckbill/flap valve or nozzle-type passive mixer were being considered as alternatives, but neither could match the efficacy of PAX's solution. PAX's main competitor manufactured a solar-powered floating draft tube mixer, but the system was up to $14,000 more expensive to install, required 24 hours of installation time, was up to 785 lbs heavier, and could only spin at 40-60 RPM. The utility's third option was a passive system, which cost $20,000 and up to install, required between 4-10 days of installation time, and weighed upwards of 200 pounds. The passive mixer could also only function 3-6 hours per day, severely limiting its efficacy at preventing stratification.

In most installations, the PAX Water Mixer can provide financial payback averaging 3-5 years. This payback is derived from the decreased dumping of aged water, decreased energy consumption, decreased chemical application, and decreased labor costs. One utility in Northern California found that seven PAX Water Mixers for its tanks would pay back in less than five years. This payback was calculated based exclusively on the cost of water that had to be dumped due to age and heat-related degradation. Not included were the other costs of troublesome tanks: increased man hours, increased testing, and increased chemical application.

Municipal water storage occurs across the entire nation, and represented an attractive business opportunity for PAX Water. Not only were the customers—municipal water companies—easy to identify, but they were also specifically interested in energy efficient, low-cost, and low-maintenance solutions. There are hundreds of thousands of eligible municipal water storage tanks in the U.S. alone.

Overcoming Challenges

One of the earliest challenges PAX Water faced in its pilot testing had to do with the fabrication process. The biomimetic geometries presented significant fabrication challenges. However, after years of experimentation and investment from the U.S. Department of Commerce through its Advanced Technology Program, PAX

Water established a robust manufacturing process that produces highly balanced, precise mixing impellers for its products.

One of the biggest obstacles to adoption for PAX Water has been skepticism from water utilities that had seen no irrevocable proof that prior attempts at mechanical mixing, using draft tube floating mixers and passive systems, had been effective. PAX Water has combated this with rigorous scientific study that quantitatively demonstrates superior performance and lower energy cost. They emphasize robust measurement to quantify performance. Establishing benchmarks to the location and unique attributes of the tank, PAX Water will perform studies in conjunction with customers. PAX Water's employees have become true domain experts who work to refine focus and provide information to those connected to the potable water industry. Their persistence has paid off, winning over many who acknowledge the unique benefits of the PAX Water approach. Jason Oppenheimer, VP of Marketing at PAX Water notes that regardless of the biomimicry excellence, domain expertise is vital.

The accuracy of modeling and testing, both internally and with third parties, is a powerful tool to assuage concerns about adopting the transformational technology PAX offers. PAX was organized so that the PAX streamlining principle could be applied to many different industries. The general research process is structured to use CFD modeling. With this design methodology, the team can begin with a desired fluid regime and reverse engineer the structure of the fan or impeller. Furthermore, accurate testing can occur within a digital laboratory, prior to the full-fledged physical testing using rapid prototypes produced from 3D models.

PAX Water has learned that developing a powerful technology and implementing applications are inseparable and vital steps. Such implementation does not always come easily. The Lily Impeller has been present in current form, since 2004, and several strategies were attempted before PAX settled on full development and sales. They soon found it too difficult to give their components to another manufacturer, who was unlikely to provide quick, accurate, and profitable results. These factors influenced PAX Water's decision to fully engineer and market their mixing product in-house. Engineering firms generally require a 5-year corporate and product history before they can specify a product for a project. This is standard practice for any entrant into a conservative business, but can make it impossible for a young company such as PAX to enter the market. Spinning off or developing within an established company, as PAX Water did, can help avoid these hurdles. Using their persistent quantitative approach, PAX was able to win over companies previously unsatisfied with mechanical mixing solutions. PAX Water has since partnered with the largest tank maintenance corporation in the U.S., Utility Services Co., who manages over 5,000 tanks. This partner acts as the primary distributor for PAX Water.

Outcomes

PAX Scientific's approach of accurate modeling and testing, both internally and with third parties, has already delivered substantial intellectual property through innovations by subsidiary companies. PAX is assembled to fund and incubate companies derived from the streamlining principle that have their own domain expertise, and would ultimately be acquired. These subsidiaries include PAX Scientific, PAX Mixer, PAX Fan, and PAX Water. Separating for these various markets provides organizational focus and a measure of firewall protection for financial and legal issues. PAX Water has led the pack with commercial delivery of products, in part because of the opportunity of the potable water market in comparison to longer term technologies such as turbines and aerodynamics.

PAX Scientific transitioned in 2005 to a multi-pronged revenue approach, from a prior licensing-based model. Based on market opportunity, some PAX innovations would be developed and marketed entirely in-house, while others would continue to be licensed in markets PAX could not directly target. PAX Water is one such integrated business, with full development occurring within the company. PAX Scientific has developed innovative technologies, and has been similarly innovative in its strategies to get those technologies to market. PAX Scientific will also engage in joint development arrangements and case-specific joint ventures. These custom business arrangements lend further flexibility to the company. The arrangement of case-by-

case flexibility and subsidiary companies insulates the parent company, PAX Scientific, from the stall or collapse the individual projects.

Company Growth

Harman and his wife, Francesca Bertone, founded PAX Scientific, Inc. around his discoveries. Fifteen angel investors initially funded the company. In the early 2000's, Harman and Bertone began hiring engineers and scientists to support their work. They also established concrete mathematical data to support the efficiency of their designs, including work by third-party labs and universities. From the 1997 founding through December 2005, PAX raised roughly $5 million from private investors. During this time, the company expanded to 20 employees. Major commercial licensing agreements began in 2003, with the first being a multi-million dollar, multi-year license of air fan technology for a variety of uses. All branches of PAX Scientific are applying major advances in fluid dynamics to the development of new projects. Now, with 17 granted patents and even more under application, PAX continues to innovate along the curve established by Jay Harman almost 15 years ago.

PAX Water has sustained growth in sales and employment. They maintained 7 employees in the first half of 2010, 10 in the second half, and currently have 12 employees. PAX Water launched their first product in 2008. In 2009, PAX Water grew by 400% over the previous year. The year 2010 saw 100% growth, and 2011 is projected at 100% growth as well. These numbers are exciting in their own right, but when considering the company was established during the recession, it becomes especially powerful. Recessionary weathering is another intangible benefit that PAX Water saw through implementing a biomimetic technology in a mindset of nature-inspired solutions. A product that completely rethinks the status quo and outperforming competitors will be seen as a worthwhile investment even in times of tight budgets. The biomimetic components, combined with flexible business approaches and rigorous prototyping, give a young company surprising resilience and success.

Lessons Learned

- Paying attention to patterns in nature can intelligently guide our design principles towards increased effiency.
- Emerging regulation, changing global economy, and government policy create fertile new ground for innovators.
- Technology enables reverse engineering of nature's genius. Reverse engineering is not limited to materials.
- Focusing on one area of nature's genius can lead to cascading innovations in related fields.
- Domain expertise is vital to encouraging customers to embrace a new design principle.

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