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INSIDE

The Insider

JOSH WOLFE, EDITOR

This edition is all about space—though not in the astrophysical sense, mind you. From digitizing our domiciles, to folding intricate forms, to calculating the compliment of a knot—this month's interviews are sure to bend your brain. We're also proud to report that several of this month's interviewees are also participants in the 3rd USA Science & Engineering Festival—the nation's most entertaining and educational science festival. Culminating in an April 2014 expo in Washing-

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Ex-Google Guy Delivers 3D Visions On-Demand

Matt Bell is co-founder and CEO of Matterport, a company building a low-cost 3D scanning platform that allows anyone to create and share accurate 3D models of indoor spaces [*Full disclosure: my venture firm Lux Capital is an equity investor*]. When Matt left **Google's** [GOOG] research team at 22, he wanted to create environments in which people interact with computers in an intuitive, natural way. Matt founded Reactrix, where he formed the technology team and provided the key computer vision innovations behind the interactive floor displays that let millions of people play with virtual koi ponds and soccer balls. When Matt first saw **Microsoft's** [MSFT] Kinect product, he recognized the huge spectrum of computer vision applications it could power. He chose to focus Matterport on building models of real things because of the potential to help millions of people communicate in 3D. When Matt isn't rallying the team at Matterport, he likes to organize community

MATT BELL

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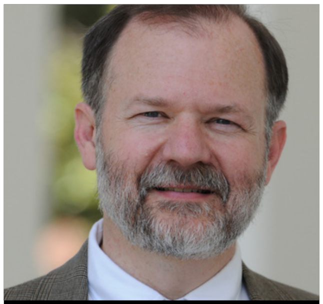
Science And Art In The Fold With Origami



DR. ROBERT J. LANG

Dr. Robert J. Lang has been an avid student of origami for more than 40 years and is now recognized as one of the world's leading masters of the art, with over 600 designs cataloged and diagrammed. Dr. Lang is also one of the pioneers of the cross-disciplinary marriage of origami with mathematics. He is noted for designs

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Tied Up In Applications For Knot Theory

COLIN ADAMS

Colin Adams is the Thomas T. Read Professor of Mathematics at Williams College. He received his Ph.D. from the University of Wisconsin-Madison in 1983. He is particularly interested in the mathematical theory of knots, their applications and their connections with hyperbolic geometry. He is the author of *The Knot Book*, an

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hacking events. Matt earned a Bachelor of Science in computer science from Stanford University.

How did you begin your career?

I went to Stanford and majored in computer science, but had a tremendous number of side passions—everything from psychology to electrical engineering. I went to Google after graduation, and it was a pretty exciting time to be at the company. There were about 200 people, and I worked on a lot of interesting machine learning problems. It was basically the largest sandbox one could possibly ask for—it dwarfed anything in academia. Google also exposed me to a range of best practices for operating a small company—everything from engineering, to hiring philosophy, to product management. My biggest passion was in computer vision though, and at the time, it was a field that wasn't in a great state.

What were some of the challenges in the computer vision world?

Ideas worked well in the lab but not in the real world. I wanted to change that, and had some ideas about how to use computer vision to bridge the digital and physical worlds, by creating camera systems that could recognize people's position and movements. I ended up leaving Google and pursuing these ideas, creating a startup called Reactrix that built interactive video projections. We deployed interactive virtual ponds and soccer fields onto the floors of malls and movie theaters. This was way before the Kinect ever existed, and it was rather exciting in the early 2000s to see people learning gesture interfaces in public places in just a few seconds. We were accomplishing our goal of bringing computers out into the physical world and allowing for that seamless interaction, where you don't even think about the fact that there's a computer there in the first place.

What is it about computer vision in particular that you believe holds so much promise?

Computer vision is basically a gateway for computers to interact in much richer ways with the physical world. We all know that computers are good at dealing with highly structured, curated information but there's a huge opportunity in enabling computers to recognize and interact with the messier visual data from the physical world. That manifests itself in everything from robotics to image capture and recognition.

When was your "A-ha" moment for starting Matterport?

I had been thinking a lot about the challenges in computer vision, and I realized that having good 3D sensors would enable many applications to work a lot better. So when the first truly low-cost 3D sensors came out in the Kinect (the sensors themselves are made by an Israeli company called PrimeSense), we realized there was a pivotal opportunity to create a new company to try to revolutionize a variety of industries using these sensors along with computer vision. In looking at the possibilities, we realized there are people in many different industries who need to work with physical spaces. The tools that they have for working with those spaces are incredibly primitive—they consist of basically taking photos and using measuring tape. These people live and breathe in three-dimensional interior spaces every day, so for them to not have a tool that is natively 3D seemed like it was a ripe opportunity for innovation.

What were some of the key early challenges in building the company?

The sensor gets you 3D snapshots, but you need to be able to put all of those 3D snapshots together in a coherent model. When we started Matterport, we found that almost all of the work that had been done in that area was lacking—the algorithms didn't work well. When building a computer vision company, you have to make sure that your algorithms will work consistently well in a wide variety of situations—everything from an empty apartment to a complex garden to the crowded engine room of a ship. So we really emphasized the development of a very robust set of algorithms that would work well across all types of situations, so our users can simply have a product that works reliably on its own.

What's the status of Matterport today?

We've now been in a beta program for several months. Since we're essentially creating an entirely new product category, we're assessing how our beta customers use our product so we can be absolutely sure we create something that's useful to a broad range of companies in a variety of industries. Initially, we've targeted

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ton, D.C., this year-round celebration of science is meant to re-invigorate the interest of our nation's youth in science, technology, engineering and math.

We begin with Matt Bell, co-founder and CEO of Matterport (full disclosure: my venture firm Lux Capital is an equity investor in Matterport). Matt shares how state-of-the-art computer vision and low-cost 3D cameras are being combined to create a brand new market in communicating 3D spaces. The company promises to make it easy to capture our physical worlds for sharing via the World Wide Web, and hopes to revolutionize everything from real estate to remodeling along the way.

Next up is Robert Lang, who has the unique distinction of being both an origami master and renowned mathematician. The connection isn't coincidental, though, as Robert pioneered the mathematical techniques that allowed for the folding of previously unfathomable forms. Dr. Lang steps us through the art and science of origami, and how the practice of folding has impacted everything from solar arrays to cardiac stents.

Lastly, we sit down with Colin Adams, an award-winning educator and erudite explorer in the world of knot theory. A study that once suffered for lack of purpose, Colin oozes enthusiasm for how terms like "hyperbolic geometry" have new relevance in untangling mysteries of DNA, uncovering new synthetic molecules, and understanding the shape of the spatial universe.

As always here's to thinking big about thinking small...and to the emerging inventors and investors who seek to profit from the unexpected and the unseen.

Ex-Google Guy Delivers 3D Visions On-Demand

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customers working with the home. The rationale behind this is some of the most important financial decisions of our lives revolve around the home—whether it's buying or selling, renting or remodeling, refurnishing or insuring—these are very big, expensive decisions people want to make sure they get right. By having a detailed 3D model of the home, we believe all of these decisions become a lot easier. We'll be moving from our beta program to a scaled rollout later this year to get our 3D scanning camera in the hands of a lot more customers.

What types of people and companies have expressed interest in Matterport's 3D camera?

A mix of professionals and companies, from individual agents to much larger enterprises. We've seen a lot of interest within the real estate industry—ranging from agents to photographers to larger commercial firms. We've also seen a specific interest in vacation rentals, since this is a situation where you often have to make a very expensive decision without visiting a location in person. We also have customers in the insurance industry who are using our product to document insurance claims in a way that is faster and much richer than what was ever possible before.

What will Matterport's camera cost?

We haven't announced a final price yet, but we expect it to be in the range of a decent digital SLR camera. There will also be a monthly charge for the cloud processing of scans, since it is a fairly computer-intensive process. Prior to the existence of Matterport, if you wanted a 3D model of a space, you had a couple of options: Hire a highly-talented 3D graphic artist who would spend several weeks taking photos, taking measurements and then recreating your space to the desired level of detail. That would cost thousands or tens of thousands of dollars. The other alternative: A 3D laser scanner, which would generally require a few days of scanning plus another 10 days aligning all of the data. Hiring a laser scanning service would cost at least $10,000, and the laser scanners themselves start around $50,000. What's great about Matterport is that we expect 3D scanning to actually be free for consumers. Because the home is typically scanned in conjunction with a large purchase decision, there is a commercial party that is motivated to help the sale, and they will typically be the ones who buy scanners or pay for the scans.

> **"This is all about helping people to communicate in 3D and enabling them to quickly manipulate 3D spaces."**

If Matterport is successful in making 3D scanning of indoor spaces widely accessible, how do you think that will change the world?

One thing that's important to understand is that 3D sensors themselves are getting smaller and cheaper very quickly. New sensors were just announced that are capable of fitting inside a tablet or smartphone. We'll soon be living in a world where everyone is effectively carrying a 3D scanner in their pocket.

Let's take a simple example: imagine one day in the near future you're shopping for furniture. You could stand in your living room, quickly wave your phone around, and then all of a sudden have a virtual model of your living room on your phone. You'd then go online and start dragging and dropping furniture from a catalog into your living room to see what it would look like. Or what if you wanted to redecorate? You could upload your 3D model to the Internet and solicit ideas and bids from designers all over the world almost instantaneously, and each of them could show you how your new living room would look.

Now imagine you're a first responder. Today, first responders rarely have much information about an emergency, and if they do have something it's usually a crude floor plan at best. What if you were a firefighter or SWAT team member and before you arrived at the scene you had a complete 3D model of the space? You'd be able to run in knowing immediately what the space would be like. I actually have a related personal experience of viewing a scanned space and then visiting it personally. While there, at one point I got up and went to the bathroom. It took me a few seconds after I reached the bathroom to realize that I'd never physically seen it before—my mental model of the space from viewing the scan had guided me right to it.

This is all about helping people to communicate in 3D and enabling them to quickly manipulate 3D spaces.

What other industries do you think you could disrupt?

Let's think about construction. It's an incredibly massive industry—something like $750 billion a year in the U.S. alone. It involves large, complex projects with the involvement of many different parties and subcontractors. Being able to take detailed physical records of the construction process lets everyone stay in sync, and it also ensures that everything is proceeding to plan. If there is a disagreement, people can quickly make annotations and clearly communicate those disagreements while viewing a shared virtual model. If we make their communication process easy, even slightly more efficient, that's a tremendous cost savings to them.

What are the next big milestones for the company, and what are you looking forward to?

We're planning a large-scale launch in late summer of this year. I'm looking forward to seeing the broad range of 3D spaces that people will scan, and to seeing the communities emerge around those spaces, as people start interacting around them online and start working with those spaces.

But we see 3D reconstruction as just the beginning of what we're offering. We've spent a great deal of effort to make sure that 3D scanning and viewing will be accessible and easy for people who are nontechnical. With Matterport, people will be able to just capture a space and have it automatically reconstructed and easily viewed and shared online—no additional work required.

Going forward, we plan to build on top of that platform, so that not only will people have easy access to 3D spaces, but they'll be able to use apps that run on top of that platform to enable a whole new level of utility. For example, if you wanted to auto-generate a floor plan, or virtually shop for furniture, those will be tools that you'll be able to invoke on our online or mobile platform. Or what if for fun, you wanted your house re-rendered and turned into a videogame as a post-apocalyptic dwelling with zombies running around? Some of those tools will be built internally, but we're also going to bring in an ecosystem of third party app developers to add additional functionality to Matterport in a wide variety of ways. **ET**

Science And Art In The Fold With Origami

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of great detail and realism, and includes in his repertoire some of the most complex origami designs ever created. His work combines aspects of the Western school of mathematical origami design with the Eastern emphasis upon line and form to yield models that are at once distinctive, elegant and challenging to fold. His work has been exhibited in museums around the world, including Paris, Los Angeles, the Kaga Museum of Origami in Japan, and the Museum of Modern Art in New York City. Dr. Lang was the first Westerner invited to address the Nippon (Japan) Origami Association's annual meeting (in 1992) and has been an invited guest at international origami conventions around the world. He has presented several refereed technical papers on origami mathematics, consulted on applications of origami to engineering problems including medical devices, air-bag design, and expandable space telescopes, and is the author or co-author of fourteen books and numerous articles on origami. Dr. Lang is a regular lecturer on the connections between origami, mathematics, science and technology. He received Caltech's highest honor, the Distinguished Alumni award, in 2009 and was elected a Fellow of the American Mathematical Society in 2013.

How did you first get started in the world of origami?

When I was a small child, I acquired a book that had some instructions for a few traditional origami designs, and I got hooked. I found no end to the possibilities within origami, all within the basic parameters of one uncut sheet of paper. Now of course there are other forms of origami that use multiple sheets, and some use cuts and I've gotten into some of that as well over time. But the primary idea of using one uncut sheet has always been the most attractive part, and that's where I have continued to find greater depth and possibility in the art.

When I was a kid, this was a way of making toys with just a sheet of paper. I could make a wide range of toys and fun shapes for free, using leftover materials or things I found. Paper was cheap and ubiquitous, so I could try things with no worries that I'd ruin it. Those factors still appeal to me but I've now added the factors of mathematical and structural beauty.

Did you intentionally decide to integrate the study of origami into your academic pursuits?

No, origami was always a hobby. When I went to Caltech for college, the plan was to have a more conventional career path in math, science or engineering—because I like to build and make things. But Caltech is a pretty challenging place that revs the brain into high gear, and it also revs up a problem-solving approach in engineering, where if you first understand the mathematical underpinning of the fundamental laws, then you can apply the tools of math to achieve the goals you're after. Origami felt amenable to that approach, in that it obeys basic mathematical laws, and we can express those laws in the language of mathematics. Most importantly, if we understand what those laws are, we can use the tools of mathematics to achieve the goals we've set—even if they are artistic goals, not engineering goals.

More simply put, by understanding and exploiting mathematical laws, we can reach an artistic vision that would otherwise be unachievable. That process got me interested in applying math to the analysis of origami, and the education that I received gave me a toolbox of mathematics that I could apply to this art.

Before you began working at this intersection of art and science, did you know of others who studied the mathematics of origami?

I wasn't aware of much other work when I started out, but since then I've learned that other people had indeed been investigating the mathematics of origami and we can find surprisingly deep roots to the mathematics of folding. Not all relate specifically to Japanese paper folding, which is what origami is, but mathematicians have worked at describing the folds on the surface of paper. Back in the 1930s, Italian mathematician Margarita Beloch looked at the mathematics of geometric constructions using folding.

The mathematics really came together starting in the late 1980s, when a group of like-minded origami researchers put together the first of what has now become a series of conferences on the mathematics and science of origami. That first conference was held in Italy in 1989 and has since been held every few years. The next is scheduled for 2014 in Japan.

Does the application of math to the art change your approach, or your perception of the limits of what you can create?

Years ago, I had lists of of things I wanted to make, but no idea how to make them. By applying new math techniques I could accomplish the goals I was after. One vision was to create horned animals, like deer. There were definitely origami deer in the past, but most used cuts. People would make a four-legged animal with a big flap on its head and then make lots of cuts in that flap to get branched antlers. I found that unsatisfying because the idea of origami was to do it all by folding. I also wanted to fold a deer that could be identified by the way the antlers branched, because different deer have different branching patterns. I started by asking how to distinguish different branching patterns, and how to quantify those features. The different arrangements of points, the different lengths and numbers, and how they're connected to one another—those all can be described mathematically.

That led to a question of the nature of paper, and how one arrangement of points is possible but another is not possible. That led to the mathematical laws and descriptions. I became interested in pursuing the more abstract question: What are the laws that determine the arrangements of points we can fold from paper? The question became purely structural and completely separate from the deer. What are the laws that let you fold this kind of structure versus that kind of structure? By creating an abstract question, you clear away all of the detail tied to a specific subject, and then you can start to perceive the underlying mathematics.

Eventually I found my way back to asking how to create a particular structure using mathematical ideas. The day that I could apply these techniques to design a deer that was recognizable as a white-tailed deer, not a mule deer, I realized I was onto something.

Some of your past work includes insects that seem like they'd be impossible to fold. How do you create these forms?

Insects are a traditional figure in the history of origami, and for years insects were considered the hardest subjects. I use the term insects informally because I'm including spi-

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> **“A whole host of origami techniques have been applied to engineering problems. One example is an arterial stent developed by a group at Oxford University.”**

ders, scorpions, crustaceans and other many-legged shapes. These were considered nearly impossible in origami, and were very generic in historical designs, even up to the 1950s and 1960s. A folded bug was sort of a blob with six legs, and getting six legs from a single sheet of paper was pretty impressive. When we started developing mathematical approaches, we made it possible to design specific types of insects. That led to an informal competition through the ‘90s—the origami bug wars, where people tried to fold ever more complicated insects. We like subjects that pose structural challenges.

Do you reach a point where designs become so intricate that you can describe the way to create a form, but have no means to actually fold it?

Oh, yes. We can design folding patterns for arbitrarily complex shapes, but the properties of the paper and of our own folding abilities limit what we can create. Two aspects limit origami: first, even the best folding paper has finite thickness that builds up until it prevents more folds. Second, some designs are so complex that you need to bring hundreds of folds together at once to make the form, and that might be too difficult to bring off.

What practical applications have emerged from our new understanding of the laws of folding?

Actually, a whole host of origami techniques have been applied to engineering problems. One example is an arterial stent developed by a group at Oxford University. Zhong You, an Oxford professor, along with post-doctorate student Kaori Kuribayashi, developed a way of folding one of these tubes into a very small package that can be threaded through the artery until it gets to the location of blockage, where it is opened out into the full tube. In the past, this type of stent existed but was made from metal mesh—the mesh tends to create blood clots, so a smooth tube is preferable.

So origami techniques have helped address heart disease! Are there other applications that come to mind?

Origami techniques have been used in space. One of the first was developed by a Japanese engineer named Koryo Miura, who developed a folding pattern that could be applied to a solar array. His array flew on a mission for the Japanese Aerospace Agency in 1995. I’m also working right now with a group at NASA’s Jet Propulsion Laboratory on a design for a different pattern for a solar array that will unfold.

If we think about the expression “form leads to function” are there areas where you believe origami could be used to improve the efficacy of existing technologies?

In general, origami can play a role when the problem requires a surface—a flat shape as opposed to a solid 3-D shape—that needs to exist in two states: one small and one big. In other words, something that needs to be small for the journey and large at the destination.

The heart stent, for example, needed to be small for the journey through the artery, but open out into a tube at the destination. Solar arrays and space structures in general need to be small in their rocket ship but then opened out at their destination. Things that are flat and sheet-like, like solar arrays, antennas, telescope lenses—anything that wants to be big and flat—these lend themselves to folding.

We’re starting to see new applications of origami in mechanisms that, for various reasons, are best made from a single sheet. One example is the creation of microscopic mechanisms, where it’s impossible to glue together little bolts and linkages. Instead, we lithographically pattern a sheet with a structure, and then fold that sheet into a mechanism that manipulates or moves in some way. More mechanical engineers are doing research specifically on the types of mechanisms that could be created by folding.

Can you describe in more detail some of these microscopic mechanisms?

One that comes to mind is a little folding manipulator for artificial insemination, where a micromechanical structure holds an egg and injects it with a single specified sperm. A microscopically machined structure uses a folding mechanism to do the grasping and the injection.

Another project, currently going on at Caltech, involves a retinal implant that is connected to an external camera, for people with macular degeneration. The external camera takes pictures of the surroundings and triggers electrical signals directly onto the retina of the person, effectively replacing the functions of their rods and cones. The user will perceive the images directly from the electrical stimulation of the retina. The electrode array that does this needs to be inserted into the eyeball in a very small package, and unfolded into a shape that conforms to the back of the eye. The Caltech team is developing an origami structure for this electrode array.

How do you go about assessing projects to understand whether folding is the best approach to solving a specific need?

In pursuing any engineering question, you explore what the requirements are to find out if an origami solution is actually the best approach, because if it’s not you’re going to be wasting your time. You can come up with an origami solution, but if the requirements of the problem don’t steer one towards a folding solution, then there’s probably a non-folding engineering technique that will work better.

What would steer one towards an origami solution? First, the material should be sheet-like, but with rigid sections that won’t flex (as opposed to cloth, that is arbitrarily flexible). You want a very well controlled deployment with a small number of degrees of freedom, so you know exactly how it is going to deploy. This is especially important in space, where you can’t go up there in person to shake out any snags. **ET**

Tied Up In Applications For Knot Theory

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elementary introduction to the mathematical theory of knots, *Why Knot?,* a mathematical comic book with attached toy, and *Riot at the Calc Exam and Other Mathematically Bent Stories*, a compendium of humorous math stories. He has written a variety of research articles on knot theory and hyperbolic 3-manifolds. He is a recipient of the Haimo National Distinguished Teaching Award from the Mathematical Association of America (MAA) in 1998, an MAA Polya Lecturer for 1998-2000, a Sigma Xi Distinguished Lecturer for 2000-2002, and the recipient of the Robert Foster Cherry Teaching Award in 2003. He is also the humor columnist for the Mathematical Intelligencer. His next book will be *Zombies & Calculus*.

How did you get started in the field of mathematics?

As a child, my goal was to become an author. I ended up at MIT, and at that point I started to fall in love with mathematics. In graduate school, I stumbled across this area of knot theory and hyperbolic volume—a professor challenged us to solve a problem for a reward of $5. I worked on it for two months, and I didn't win, but it set the course for my Ph.D.

Can you explain, in layman's terms, the concepts of knot theory and hyperbolic volume?

Hyperbolic volume is a quantity that we associate to a knot. Mathematically, when we talk about a knot, we imagine a string with a knot tied in the middle, and the two loose ends glued together, trapping that knot on the string. The most fundamental question we can ask in knot theory is whether we could disentangle that piece of string, without cutting the string?

Depending on how complicated the knot was, you could play with it for years without success. You need mathematical techniques to decide whether it's possible to disentangle the string.

How does the volume of a knot relate to its fundamental construction?

The volume component is where it gets a little more technical. First, let's define the *compliment* of the knot, which is space, minus the knot. That gives us a topological space, and we measure distance on that topological space in a way that is negatively curved, and that makes it hyperbolic. Hyperbolic really just means negatively curved. In this way, we measure the knot's hyperbolic volume: the volume of space minus the knot. Now, you might think that's got to be infinite, because space is infinite and space minus the knot is going to be infinite, right? As it turns out, measuring distance that's negatively curved will give you a finite volume.

And so we can associate a finite, hyperbolic volume to each knot, which gives us a way to distinguish between the knots. If I give you two knots and you calculate the hyperbolic volume of one knot to be 2.713 and the other knot to be 4.614, then you know that those two knots are distinct, and you cannot rearrange the one to look like the other.

What is one of the most basic knots you can study?

If you take a string and tie a simple overhand knot, and then you glue the two loose ends together, you get a knot with three crossings on it. That's called the trefoil knot, and that's the first nontrivial knot that cannot be disentangled.

However, we can make knots that are arbitrarily complicated, at least in appearance, which in fact could be disentangled. Imagine taking a string that is three miles long and gluing the ends together, and then messing it up and tangling it into a horrendous ball of string, an absolute disaster that would take six months to disentangle. That would be an example of a trivial knot in a very nontrivial configuration.

Is knot theory a new field of study?

Knot theory dates back about 140 years, back to the days when people were trying to come up with a model for the atom. They were asking questions like "How do we distinguish between gold and lead? What is the fundamental difference between those?" At that time they believed that there was this ether that pervaded all of space, and that atoms were just little knots in the ether.

They thought that a table of distinct knots would actually be a table of the elements, which would help distinguish between the different atoms.The whole knots-in-ether theory ended in the late 1880s, when the Michelson-Morley experiment showed that there was no ether, in fact.

What kept the field alive?

Mathematicians continued to work on knot theory simply because of the beauty of the field, but it was a bit of a backwater for the next century. By the 1980s, people discovered important applications of knot theory, including how it relates to DNA. DNA is a long, skinny, string-like molecule with a double helix structure, which has been stuffed into the nucleus of the cell. It's the equivalent of stuffing 200 kilometers of fishing line into a basketball; it's this horrendous tangle, yet it has to be able to do recombination, transcription and various other things for the cell to function properly. If it's all tangled up, how can the DNA make copies of itself that can be separated out?

Well, what's the biological solution to the DNA knot problem?

As it turns out, inside the nucleus there are enzyme molecules able to cut one DNA strand open to pull another strand through, close the first one up and then let them go. In knot theory parlance, the enzymes are making what's called a crossing change, where one strand is allowed to pass through another. The knot is changed in a way that allows the DNA to disentangle. In essence, the whole field of protein theory is really a lot of knot theory—studying how proteins knot and unknot.

What additional areas of study relate to knot theory?

Knot theory also applies to synthetic chemistry—synthesizing new molecules. Think about any long, skinny molecule that comes around and bites its own tail to form a cyclic molecule. Benzene is a classic example of a cyclic molecule. If you take that cyclic mole-

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cule, cut it open, tie a knot in it, and then glue the two loose ends together, then you've formed a knotted molecule. Synthetic chemists are incredibly excited about synthesizing knotted molecules, which use the same constituent atoms bonded in exactly the same order. By adding a knot, it has completely different properties than the unknotted version. This means we could create a limitless supply of new substances, because of the large number of distinct knots. For example, if I drew a picture of a knot with 16 crossings, we know there are more than 1,700,000 different knot possibilities. If you have a long enough molecule and you know how to knot on the molecular level, you could make over 1,700,000 different substances out of that single sequence of atoms! This concept holds incredible potential for dramatically expanding the set of substances that can be created with just one chain of atoms.

> **"Synthetic chemists are incredibly excited about synthesizing knotted molecules…by adding a knot, it has completely different properties than the unknotted version. This means we could create a limitless supply of new substances."**

Is this still a theoretical process, or are researchers successfully knotting molecules into new configurations?

So far, they've been able to synthesize trefoil knots, and they've been able to synthesize five crossing knots, but they have not yet found a good system for synthesizing more complicated knots. They're still working on designing some kind of a template that allows the separate creation of little pieces of knots that can be brought together when the template is dissolved. There are still very few actual knotted molecules, so we don't yet have many examples where we can say, "Here is this brand new substance that is particularly useful for this specific purpose." Yet the knotted versions seem to behave completely differently, and a lot of research dollars are supporting efforts to learn more about these possibilities.

Let's go back to education for a moment. What excites you about teaching?

I'm lucky to teach in a place like Williams College. The students are fantastic, and I love to see their eyes light up when they understand and get excited by the mathematics. I enjoy coming up with new and unusual ways to teach math, to get the messages across. That can mean a lot of different things in the classroom. It means coming up with innovative classes for students and ways to get people's attention. For instance, I've created a series of silly, tongue-in-cheek videos—the goal is to get people to pay attention long enough to see the beauty in these important mathematical concepts.

Would you share your thoughts on being involved with the USA Science and Engineering Festival?

It's a great opportunity to reach out to a group of kids who have tremendous potential, and excite them about science and mathematics. It's critical to get young people interested in science. We're now competing with television, video games and various other opportunities that students can access. If we can't keep their interest it's going to be disastrous in the long run, so the key is to come up with ways to get people to pay attention long enough for them to get excited about the science.

What is your perspective on the current state of math and science education in the U.S.?

At the college and graduate level, we have the best schools in the world. People come to the United States from all over the world to go to graduate school in math and science. Our colleges are very successful, some more than others, but overall science and math at the college level is quite good. At the high school level we struggle more. One challenge is to get enough people at that level who are both strong in teaching and in the sciences, when the monetary rewards are low and the frustration can be high. Often they work with students who come into high school unprepared, and it becomes difficult to take them to the next level. Mathematics, in particular, is very cumulative. A student who has a bad experience early on, or who misses one important chunk, can have a hard time making that up later. That lag builds quickly and can become a disaster. We lose a lot of students that way.

Outside of knot theory, what are some other fields that you think are really exciting right now?

These days, I'm intrigued by a question in the field of cosmology, which is related to knot theory mathematics. The question asks,"What is the shape of the spatial universe in which we live?"

Thousands of years ago, humans didn't know that our planet is a sphere. Locally, it looked essentially two-dimensional. The Greeks figured out one of the great victories of human intellectual history: that the surface of the earth is a sphere, as opposed to a plane that goes on forever or a disk where we could fall off the edge.

Our next great intellectual achievement is to determine the shape of the universe. One might expect a three-dimensional space going on forever in every direction, yet in fact very few cosmologists think that's the case. Most cosmologists believe that the universe is finite, yet you can head in any one direction forever.

How would such an arrangement of space be possible?

Imagine a cube. What if I could glue the left face to the right face, the front face to the back face and the top face to the bottom face, so I've glued them all around. I couldn't actually stretch a cube around like that, but just imagine it in the abstract. So if we head out the right face, we'd come back in on the left; head out the front face, come back in on the back, and so on. That shape is called a three torus. If that cube is the universe, imagine flying straight out of our galaxy. You'd eventually fly right back into the place you left!

To study the shape of the universe, we have a satellite that is collecting data from the cosmic microwave background radiation. That may give us enough information to conceivably determine the shape of the universe. To me, that's a really cool problem. **ET**

The Emerging Tech Portfolio

Company[symbol]	Coverage Initiated	Current Price	52-week range	Mkt Cap ($mil)
INTELLECTUAL PROPERTY INCUMBENTS Leading researchers in the physical sciences, with big potential for spin-offs and revolutionary breakthroughs				
GE [GE]	8/07	$23.37	$18.02-$23.90	$243,010.00
Hewlett-Packard [HPQ]	3/02	19.20	11.35-25.40	44,790.00
IBM [IBM]	3/02	212.08	181.85-215.90	236,370.00
LIFE SCIENCES Companies that are working at the cutting edge of medical technology				
Life Technologies [LIFE]	11/05	63.99	39.73-65.84	10,900.00
Nanosphere [NSPH]	11/07	2.20	1.51-3.89	122.74
ELECTRONICS Companies that have corralled the key intellectual property that will be the foundation for next generation electronics				
Nanosys [private]	3/02	n/a	n/a	n/a
ENERGY Companies that are developing high-efficiency, low-cost alternative energy technologies				
First Solar [FSLR]	8/07	28.85	11.43-36.98	2,510.00
ENABLING TECHNOLOGIES Tools and instrumentation that enable critical science and technology discoveries				
Veeco [VECO]	3/02	34.96	26.15-38.39	1,350.00
FEI Company [FEIC]	1/03	63.75	42.18-65.29	2,460.00
Accelrys [ACCL]	3/02	9.66	7.44-9.97	537.21
INVESTMENT VEHICLES Funds that have investments in promising emerging technology companies				
Harris & Harris Group [TINY]	5/02	3.64	2.98-4.57	111.91
PowerShares Lux Nanotech Portfolio [PXN]	8/07	6.30	5.41-6.85	18.13
PowerShares WilderHill Clean Energy [PBW]	8/07	4.58	3.46-5.78	140.87

Stock prices as of March 22, 2013

Word on the Street

GE: Shares hit a new 52-week high before ending flat on the month. Investors see the company as a proxy for the global economic recovery and increased capital expenditures.

HPQ: HP zoomed 20% higher as investors begin to believe in CEO Meg Whitman's turnaround plans. The board also increased HP's quarterly dividend 10% to 14.52 cents per share. While the company still faces huge headwinds, the stock is now up 62% YTD and has almost doubled from its November 2012 low. Morgan Stanley raised its rating to Overweight (from Equal Weight) and set a $27 price target. Revenue is expected to fall 6% in the current fiscal year (ending in October), after a 5.4% decline last year. HP trades at 6.5x this year's expected $3.45 in EPS.

IBM: Big Blue advanced nearly 5.5%, reaching an all-time high, which now values the world's largest provider of computer services at more than $236B. Shares have climbed 11% this year, boosted by EPS gains, divestures of underperforming units, and a move into higher-margin software businesses like data analytics. IBM has said it will deliver at least $20 in 2015 EPS, compared with $15.25 last year. It also has set aside $50B billion for share repurchases and $20B for dividends. The stock still trades at a 10% discount to the P/E of the S&P 500.

LIFE: Life Technologies closed nearly 10% higher as buyout rumors reached a fevered pitch. The latest word is that M&A discussions have shifted in favor of strategic buyers as some private equity firms drop out. The odds are reportedly growing that either **Danaher** [DHR] or **Thermo Fisher Scientific** [TMO] could buy Life, as KKR, Blackstone, TPG and Carlyle have apparently withdrawn from the process. Cowen & Co. downgraded LIFE shares to Neutral (from Outperform) based on the expectation that the likely sale price won't be much higher than the current trading price. Analysts expect LIFE to earn $4.37 per share in 2013.

NSPH: Nanosphere rose 12.2% after brokerage firm Canaccord upgraded NSPH to a Buy rating, claiming shares were oversold and there was 150% upside. The firm believes that Nanosphere is poised to capture a large piece of the molecular diagnostics business after it shifted its focus to blood stream infections. Nanosphere obtained the CE Mark for its Gram-Negative Blood Culture Test. The Gram-Negative Blood Culture test notably expands Nanosphere's infectious disease test capabilities to include rapid detection of bacteria that can cause deadly bloodstream infections, an increasingly recognized health threat.

FSLR: First Solar shares lost 14.7% of their value after reporting disappointing Q4 results and guiding lower for 2013. First Solar earned $1.74 per share on revenue of $1.1B in Q4 2012, below analysts' projected profit of $1.75 per share on revenue of $1.3B. The company said Q1 will fall far short of expectations, guiding to revenues of just $650-750M (versus forecasts of $822M) and EPS of $0.70-0.90 (versus forecasts of $0.89). Bank of America Merrill Lynch cut its rating to Underperform and lowered the price target to $25 (from $35). RW Baird also downgraded the stock to Neutral with a $25 price target. Goldman Sachs reiterated its Neutral rating, but cut the price target to $27.

VECO: Veeco jumped 17.9% as investors anticipate a strong rebound in the LED equipment market. The company received a letter from the NASDAQ on March 5 notifying Veeco that it is not in compliance with Listing Rule 5250(c)(1) because its 2012 Form 10-K was not filed on a timely basis with the SEC. As previously announced, the Form 10-K, as well as the company's Q3 report on Form 10-Q could not be filed timely because the company is reviewing the timing of revenue recognition of MOCVD systems and related upgrades to these systems. Northland Capital initiated coverage on Veeco with a Market Perform rating and a $29 price target.

FEIC: FEI shares edged higher on no news. Shares are up more than 15% YTD.

ACCL: Accelrys eclipsed a new 52-week high before slipping almost 2% after reporting fourth quarter results. Q4 non-GAAP revenue increased 16% to $47.5M. Non-GAAP net income was $4.5M ($0.08 per share), compared to $4.6M ($0.08 per share) for the prior year period. Analysts had expected revenue of $43.5M and EPS of $0.07. Accelrys recently completed three acquisitions (HEOS, Aegis Analytical Corp. and Vialis AG) that complicate its GAAP financials. The company said the acquisitions have helped position Accelrys as the leading provider of scientific innovation lifecycle management software. For FY 2013, Accelrys expects non-GAAP revenue of $185-190M, and non-GAAP EPS of $0.36-$0.39.

TINY: Harris & Harris Group nudged lower after reporting Q4 2012 results. The firm's Net Asset Value fell to $4.13, versus $4.70 a year earlier. Most of that was attributable to the decline in **Solazyme** [SZYM], its largest holding. TINY exited its entire investment in **Neophotonics** [NPTN] and began selling Solazyme shares.

PXN: The PowerShares Lux Nanotech portfolio advanced almost 5% on the month.

PBW: The PowerSharesWilderHill Clean Energy portfolio fell 4.2%.

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