PHYSICS ON TWO WHEELS

Jim Papadopoulos has spent a lifetime pondering bicycles in motion. His work, once nearly lost, has found fresh momentum.

BY BRENDAN BORRELL
Seven bikes lean against the wall of Jim Papadopoulos’s basement in Boston, Massachusetts. Their paint is scratched, their tyres flat. The handmade frame that he got as a wedding present is coated in fine dust. “I got rid of most of my research bikes when I moved,” he says. The bicycles that he kept are those that mean something to him. “These are the ones I rode.”

Papadopoulos, who is 62, has spent much of his life fascinated by bikes, often to the exclusion of everything else. He competed in amateur races while a teenager and at university, but his obsession ran deeper. He could never ride a bike without pondering the mathematical mysteries that it contained. Chief among them: What unseen forces allow a rider to balance while pedalling? Why must one initially steer right in order to lean and turn left? And how does a bike stabilize itself when propelled without a rider?

He studied these questions intensely as a young engineer at Cornell University in Ithaca, New York. But he failed to publish most of his ideas — and eventually drifted out of academia. By the late 1990s, he was working for a company that makes the machines that manufacture toilet paper. “In the end, if no one ever finds your work, then it was pointless,” he says.

But then someone did find his work. In 2003, his old friend and collaborator from Cornell, engineer Andy Ruina, called him up. A scientist from the Netherlands, Arend Schwab, had come to his lab to resurrect the team’s research on bicycle stability.

“Jim, you need to be a part of this,” Ruina told him.

TWO WHEELS GOOD

Together, the researchers went on to crack a century-old debate about what allows a bicycle without a rider to balance itself, publishing in Proceedings of the Royal Society1 and Science2. They have sought to inject a new level of science into the US$50-billion global cycling industry, one that has relied more on intuition and experience than on hard mathematics. Their findings could spur some much needed innovation — perhaps helping designers to create a new generation of pedal and electric bikes that are more stable and safer to ride. Insights from bicycles also have the potential to transfer to other fields, such as prosthetics and robotics.

“Everybody knows how to ride a bike, but nobody knows how we ride bikes,” says Mont Sommerfeld, a teacher from the Netherlands, in his memoir, published 40 years later, he counted the observation as one of his great accomplishments. “I am now hailed as the father of modern bicycle theory,” he declared.

A bicycle’s front wheel can act as a caster because the point at which the wheel contacts the ground typically sits anywhere from 5 centimetres to 10 centimetres behind the steering axis (see “What keeps a riderless bike upright?”). This distance is known as the trail. Jones discovered that a bike with too much trail was so stable that it was awkward to ride, whereas one with negative trail was a death trap and would send you tumbling the moment you released the handlebars.

When a bicycle starts to topple, he concluded, the caster effect steers the front end back under the falling weight, keeping the bicycle upright. To Jones, the caster trail was the sole explanation for a bike’s self-stability. In his memoir, published 40 years later, he counted the observation as one of his great accomplishments. “I am now hailed as the father of modern bicycle theory,” he declared.

GEARING UP

That article would make an impression on Jim Papadopoulos, then a teenager in Corvallis, Oregon, with a gift for numbers and a home life in tatters. In 1967, his father Michael, an applied mathematician from England, started a job at Oregon State University. But Michael Papadopoulos was denied tenure after protest-

Jim Papadopoulos sees a future with radically new bicycle designs.

For a mechanician — that fusty breed of engineer whose subject is defined by Newton’s three laws of motion — the conundrums of the bicycle hold a special allure. “We are all stuck in the nineteenth century, when there wasn’t such a difference between math and physics and engineering,” says Ruina. Bicycles, he says, are “a math problem that happens to relate to something you can see”.

The first patents for the velocipede, a two-wheeled precursor to the bike, date to 1818. Bikes evolved by trial and error, and by the early twentieth century they looked much as they do today. But very few people had thought about how — and why — they work. William Rankine, a Scottish engineer who had analysed the steam engine, was the first to remark, in 1869, on the phenomenon of ‘countersteering’, whereby the rider can steer to the left only by first briefly torquing the handlebars to the right, allowing the bike to fall into a leftward lean.

The link between leaning and steering gives rise to the bicycle’s most curious feature: the way that it can balance while coasting on its own. Give a riderless bike a shove and it may wend and wobble, but it will usually recover its forward trajectory. In 1899, English mathematician Francis Whipple derived one of the earliest and most enduring mathematical models of a bicycle, which could be used to explore this self-stability. Whipple modelled the bicycle as four rigid objects — two wheels, a frame with the rider and the front fork with handlebars — all connected by two axles and a hinge that are acted upon by gravity.

Plugging the measurements of a particular bicycle into the model revealed its path during motion, like a frame-by-frame animation. An engineer could then use a technique called eigenvalue analysis to investigate the stability of the bicycle as one might do with an aeroplane design. In 1910, relying on such an analysis, the mathematicians Felix Klein and Fritz Noether along with the theoretical physicist Arnold Sommerfeld focused on the contribution of the gyroscopic effect — the tendency of a spinning wheel to resist tilting. Push a bicycle over to the left and the rapidly spinning front wheel will turn left, potentially keeping the bicycle upright.

In April 1970, chemist and popular-sciencewriter David Jones demolished this theory in an article for Physics Today3 in which he described riding a series of theoretically unrideable bikes. One bike that Jones built had a counter-rotating wheel on its front end that would effectively cancel out the gyroscopic effect. But he had little problem riding it hands-free.

This discovery sent him hunting for another force that could be at play. He compared a bike’s front wheel to the casters on a shopping trolley, which turn to follow the direction of motion.

“EVERYBODY KNOWS HOW TO RIDE A BIKE, BUT NO ONE KNOWS HOW WE RIDE BIKES.”
WHAT KEEPS A RIDERLESS BIKE UPRIGHT?

Scientists have grappled with this question for decades. How does a bike moving forward without a rider stay upright? Even when struck from the side, it will correct its course and regain stability.

THE WEIGHT DISTRIBUTION

Bicycle researcher Jim Papadopoulos found these explanations incomplete: with the right weight distribution, a bicycle with a negative trail and counter-spinning wheels to cancel the gyroscopic effect can still be self-stable. His collaborators have built a bike to test some of these ideas.

THE GYROSCOPIC EFFECT

A spinning wheel will resist falling over and transfer tilting force into a turn. This could help to right a bike.

THE CASTER TRAIL

A bicycle’s front-wheel steering axis sits slightly ahead of the point at which the wheel touches the ground, creating a ‘trail’ like that of an office-chair caster. This means the wheel will turn in the direction the bike is travelling (or falling, as the case may be).

工程学硕士Jim Papadopoulos在剑桥的麻省理工学院（MIT）攻读了博士学位，并在骨折力学方面进行研究。Papadopoulos的导师Michael Cleary对他的研究持乐观态度。他说：“我认为Ji将成为大学教授，而且我相信它会在这里。”他说。他告诉Exxon内部杂志的一位撰稿人。

Papadopoulos有不同的观点。他一直在研究Whipple的模型和Jones的文章，而且在夏季，他曾到MIT的一个小角落实习。

Papadopoulos和Ruina成了好朋友。当Ruina在Cornell大学工作时，他雇佣了Papadopoulos作为博士后。他们谈到自行车时，他并没有想要做出任何严肃的事情， Ruina说。

Papadopoulos说服Ruina认为自行车公司——就像石油公司——可能会有兴趣支持学术研究。所以他开始募集资金，扩大自行车市场。对于5000美元，他们可以是Cornell自行车研究项目，一个雄心勃勃的努力，将研究从车轮强度的破裂。
first author. “I find much more joy discovering the new and working out the details and, of course, it’s boring to write it up,” he says. Without money or publications, his time in bicycle research wound down. In 1989, he put his bikes into a moving van and drove west to Illinois, where his then-wife had a job. He endured a succession of teaching and industry jobs that he hated. In his spare time, he founded and moderated the Hardcore Bicycle Science e-mail list for bicycle-science nerds and helped to build a car that fitted into a few suitcases for the reality television show Junkyard Wars.

In 2001, David Wilson, an MIT engineer and inventor of one of the first modern recumbent bicycles, invited Papadopoulos to co-author the third edition of the book Bicycling Science. Papadopoulos was overwhelmed by monetary debts and responsibilities. He failed to send Wilson the first chapter, and then stopped responding to e-mails altogether. Wilson felt betrayed. “He is a rather brilliant guy,” Wilson says, but “he always had problems finishing anything.” Papadopoulos says that he did complete the work, but that it took two years longer than it should have, partly because of a stressful divorce.

BACK TO THE BIKE
At Cornell, Ruina moved on. He applied the team's insights about bicycles to a new arena: robots. If bicycles could demonstrate such elegant stability without a control system, he reasoned, it might be possible to design a stripped-down walking machine that achieves the same thing. In 1998, he worked with Martijn Wisse, a graduate student of Schwab's at the Delft University of Technology in the Netherlands, to build a bipedal machine that could walk down a slight incline with no motor at all, storing energy in its swinging arms. Adding a few electronic motors generated an energy-efficient robot that could walk on level ground.

In 2002, Schwab decided to spend his sabbatical with Ruina, and they started discussing the old bicycle work. It was then that Ruina called Papadopoulos and paid for him to visit. “That was the first time I met the genius,” says Schwab.

With more bicycles on the road than ever before, Schwab found it inconceivable that no one had published the correct set of bicycle equations, or applied it to bicycle design challenges. Within a year, he and Jaap Meijaard, an engineer now at the University of Twente in the Netherlands, independently derived their own equations and found complete concordance with Papadopoulos's. They presented the definitive bicycle equations at an engineering conference in South Korea, and the four collaborators published them jointly.

The challenge now was to prove that it was more than just a mathematical finding. Schwab and a student spent a year building a self-stable bike with a very small negative trail. Looking like the offspring of a razor scooter and a seesaw, it had a weight angled out in front of the front wheel and a counter-turning wheel to cancel out gyroscopic effects. In a video of it coasting, you can see it lean and veer to the right, but then recover on its own. The experiment proved that Papadopoulos had been right about the complex interplay of factors that make a bicycle stable or unstable.

Yet, after waiting for three decades for his discoveries to reach a wider audience, Papadopoulos can't help but feel deflated. “It did not change everything in the way that we imagined,” he says. This year's bike frames look much like last year's. “Everyone is still in the box,” he says. Nevertheless, other researchers have since been pulled into the group's orbit, creating enough momentum to launch a Bicycle and Motorcycle Dynamics conference in 2010. It gathers together tinkerers from all over the world, some of whom have also built weird experimental bicycles to test design principles.

One of the organizers of this year's conference, engineer Jason Moore of the University of California, Davis, has sought to probe the link between a bicycle frame's geometry and an objective measure of handling — its ease of control. The work was inspired by extensive military research on aircraft pilots. Moore created a model of human control by performing various manoeuvres on bikes fitted out with sensors to monitor his steering, lean and speed. To force himself to balance and ride using steering movements alone (rather than shifting his weight), he had to don a rigid upper-body harness that bound him to the bike. The research confirmed the long-standing assumption that more stable bikes handle better, and potentially gives frame builders a tool to optimize their designs.

It also introduced a puzzle: the steering torque required was two or three times that predicted by the Whipple bicycle model. This might have been caused by friction and flexing of the tyres, which are not part of the model, but no one is certain. For further tests, Moore and his colleagues have built a robotic bike that can balance itself. “Once you have a robot bicycle, you can do a lot of crazy experiments without having to put a human in danger,” he says. (One of his earlier handling experiments had him regaining his balance after a sideways blow from a wooden stick.) Unlike many other riderless-bike robots, it does not use internal gyroscopes to stay upright, but depends on steering alone. Moore has shipped it to Schwab for further study.

Today, Schwab has the kind of laboratory that Papadopoulos always dreamed of, and Papadopoulos is grateful to be able to collaborate. “It’s the most beautiful thing you can imagine,” he says. Schwab's other projects include a 'steer by wire' bike, which allows him to separate steering movements from balancing ones, and a 'steer assist' bicycle, which stabilizes itself at slow speeds. He has also identified a rear-steered recumbent bike that shows self-stability, in part owing to an enlarged front wheel that boosts gyroscopic effects. The chief advantage of a rear-steered recumbent is that it would have a shorter chain than standard recumbents, which should lead to better energy transfer. “People have tried to build them before, but they were unrideable,” Schwab says.

Brendan Borrell is a journalist in New York City.

CORRECTION
The News Feature ‘Physics on two wheels’ (Nature 535, 338–341; 2016) contained several biographical inaccuracies. Michael Papadopoulos moved his family to the United States more than a decade before taking a job at Oregon, not in 1967. Jim Papadopoulos spent a whole academic year at Oregon before starting at MIT. He did not write to bike companies asking for work until the 1990s. His time at the US Geological Survey was part of an internship, not a full-time job. The e-mail list he moderated was also founded by him, and is called Hardcore Bicycle Science. He has actually published three first-author papers, but just one related to bicycle science. He was also not given a chance to respond to a comment about his ability to finish things.