SPRING / SUMMER
2017

ENGINEERING PHYSICS

UNIVERSITY OF WISCONSIN-MADISON

COMPUTER MODELS FOR NONLINEAR DESIGNS

Douglass Henderson

GREETINGS!

As we close out another successful academic year, there are many accomplishments to reflect on and exciting opportunities on the horizon.

We are fortunate to have an exceptional group of faculty in the engineering physics department. It's affirming to have this talent also recognized through awarded professorships that continue to grow the reputation of the department and honor outstanding faculty. I'm happy to announce that Todd Allen has received the Grainger Institute for Engineering Professorship. Named professorships provide faculty members with flexible funds that support efforts such as the groundwork of bold new research ventures, and educational innovation—activities not supported by conventional research grants.

Many of our faculty are involved in public policy and national dialogue around important issues, such as the future of nuclear innovation. The University of Pennsylvania Think Tanks and Civil Societies Program selected a report co-authored by Todd as one of the top 50 worldwide policy study-reports produced by a think tank in 2016. He produced the report, "A step-by-step guide to nuclear innovation policy," for the Third Way think tank, where he was a senior visiting fellow during his sabbatical. It's a pleasure to have Todd back on campus. You can read about his important role with the Grainger Institute for Engineering on the back cover.

Longtime faculty member Dan Kammer has announced his retirement. Dan has been a core faculty member for the astronautics option and has taught astronautics courses for many years. In addition, Dan is the faculty advisor for the American Institute of Aeronautics and Astronautics UW-Madison chapter, and is the department's advisor for the interdisciplinary, cross-college Applied Mathematics, Engineering, and Physics (AMEP) program in the College of Letters and Science. The department will miss his many contributions and experienced wisdom.

The department's successful 2016 giving campaign drew engagement from both young alumni and those many years out of school who haven't been engaged with the department in years. These donations make a significant impact and help ensure the continued success of our department. You can always give online at allwaysforward.org/giveto/ep or reach out to our development director, Aaron Mullins, at aaron.mullins@supportuw.org, who can share many additional ways in which your donation can be used.

Thank you for your involvement and support of our department. ON, WISCONSIN!

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SPINOFF RECEIVES $10 MILLION TO PRODUCE CRITICAL MEDICAL ISOTOPE

SHINE Medical Technologies, Inc. of Janesville, Wisconsin, has been awarded $10 million from the U.S. Department of Energy to advance production of an isotope used to diagnose heart disease and cancer.

SHINE's technology eliminates the use of highly enriched uranium in making molybdenum-99, an isotope that decays into one that is used in more than 40 million medical imaging procedures annually.

The funding will advance the design and construction of SHINE's radioisotope production facility in Janesville. "We are grateful to the DOE National Nuclear Security Administration for its financial and technical support through the construction permit approval process," said Greg Piefer *(pictured)*, SHINE CEO.

Piefer invented the essential technology while earning a PhD in nuclear engineering and engineering physics at UW-Madison.

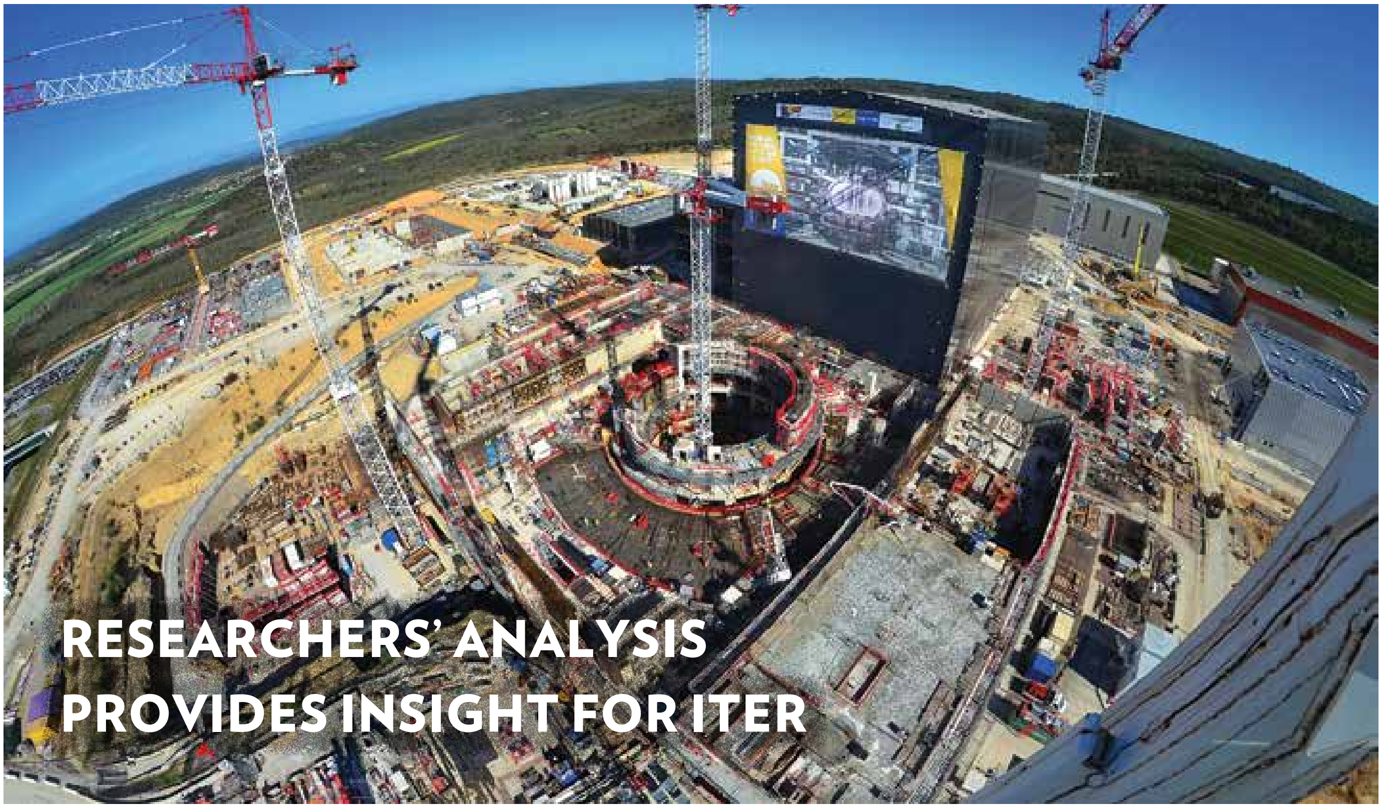


Photo courtesy of the ITER Organization

RESEARCHERS' ANALYSIS PROVIDES INSIGHT FOR ITER

Paul Wilson

While the ITER facility under construction in southern France is still years away from being completed, the ITER Organization already knows what radiation levels to expect within the building following fusion experiments—and as a result, how to keep people in the building safe—thanks to the work of UW-Madison engineers.

Once the massive construction and assembly efforts are completed, the ITER building will house the world's largest tokamak, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy based on the same principle that powers the sun and stars.

For more than a decade, Grainger Professor of Nuclear Engineering Paul Wilson and his collaborators have been developing software tools to model complex nuclear energy systems. And since ITER will be the most complex nuclear fusion system ever created, it offered an excellent opportunity for Wilson and his students to apply their software tools to solve a difficult problem.

They used these tools to estimate the radiation levels within the entire ITER building after the reactor is shut down. "It was a really big effort," Wilson says. "However, UW-Madison is one of the leading places in the country to do an analysis of ITER."

Wilson says calculating radiation levels is important for the safety of workers who will be maintaining the ITER equipment. "And since ITER is in the process of being built, our work is influencing the design and maintenance schedules of the equipment," he says.

For example, since the ITER engineers know what the radiation level inside the building will be, they can determine how long technicians can safely work inside the building to maintain the equipment. As a result, if maintenance for a certain piece of equipment will require more than the allotted time, ITER might need to make changes to that component to, for instance, allow workers to easily disconnect it and remove it from the room so they can perform the maintenance in a safe place.

Wilson's software tools are exceptional at analyzing objects with very complex geometries—and importantly, those geometries can originate from a CAD (computer-aided design) model developed using standard CAD software. Wilson's tools can consume these CAD models and produce a computational model for a full, detailed analysis.

For the ITER project, Wilson and his team took the individual CAD models provided by the designers of the ITER tokamak building and assembled them all into a large model.

Fusion experiments in ITER will produce neutrons, and Wilson and his students used their tools along with software from Los Alamos National Laboratory to map how those neutrons spread inside the tokamak building.

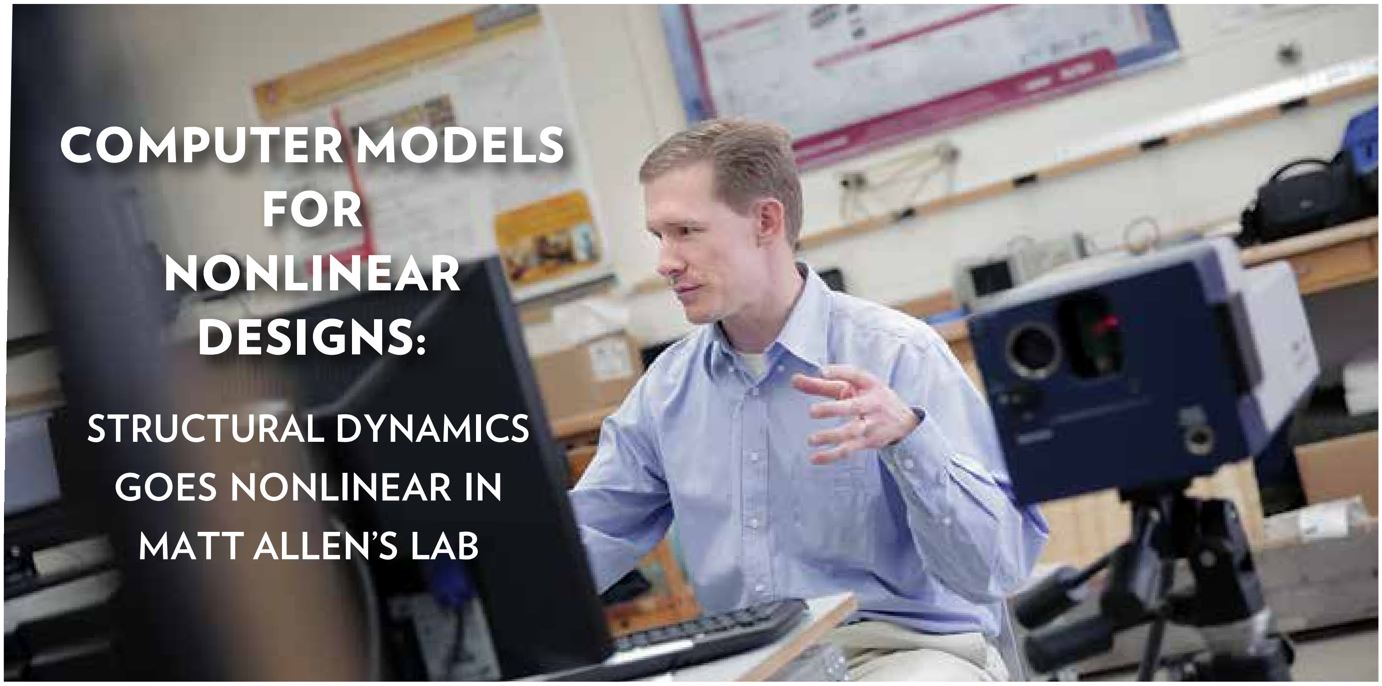
"We've got this big, cathedral-sized building full of slightly radioactive material," Wilson says. "We ran simulations with additional software on our model to figure out how much radiation there is everywhere in the building from that material."

Wilson's tools can dramatically speed up the process of producing a model that engineers can use for a comprehensive analysis.

"In the absence of our software, someone has to take this complex CAD geometry and figure out how to manually represent it, and it can take a person months to do that," he says. "And so we're providing a capability where, in the best case, it takes only days of time to make the models usable. In the most complex cases, it could take weeks or even months, but it'd still be many fewer months than with the manual process."

COMPUTER MODELS FOR NONLINEAR DESIGNS:

STRUCTURAL DYNAMICS GOES NONLINEAR IN MATT ALLEN'S LAB



Photos: Stephanie Precourt

Matt Allen is working on developing a set of tools that will allow engineers to accurately predict the response of nonlinear structures. This will enable industry to be more aggressive in design and even exploit nonlinearity to make quieter, more durable structures.

Among his many research, teaching and outreach duties, Associate Professor Matt Allen shoots lasers at a traditional East Asian gong in the name of science.

Allen, who leads the Structural Dynamics Lab, hopes his gong research will help the U.S. Air Force in its effort to develop an aircraft that could reach hypersonic speeds more than five times the speed of sound.

But what can a gong possibly have to do with hypersonic aircraft? The relationship is nonlinear, so to speak.

Allen studies the mind-boggling complexities of nonlinear structural dynamics. Specifically, Allen is interested in nonlinear vibrations and in experimentally characterizing and accurately modeling those complex vibrations. That's what the gong is for.

When Allen taps the gong softly, it vibrates at a single, linear, predictable frequency. But if he winds up and really whacks the gong, the tone transforms into a cacophony of different frequencies. These frequencies are exceedingly difficult to predict, or even measure, because they come about due to nonlinear vibration of the gong. This is where the laser becomes handy—when aimed at the gong, the laser precisely measures the nonlinear vibrations associated with the multiple tones. Allen is working to compare those measurements with computer models in hopes that one day they will be able to account for the nonlinear vibrations like these. He aims to accurately predict how a structure like this will move and how its sound will radiate.

That's important because vibration is destructive, and nonlinear vibration is potentially even more so because of its unpredictability.

But what does all of this have to do with hypersonic aircraft?

Allen explains that modeling the nonlinear vibrations of the gong is a first step toward understanding how similar nonlinear vibrations would affect the thin skin panels on an advanced aircraft that would be subject to huge and fluctuating air pressures. In the past, engineers have tried to design these aircraft so the panels are stiff and the vibrations stay small and linear, but at hypersonic speeds the pressures are so large that it has proven impossible to design a structure that is both light enough to carry the required fuel and stiff enough to remain linear. Allen hopes that by understanding, and eventually exploiting, nonlinearity, his research can open up a whole new world of possibilities.

"We hope that we can understand how to use thin panels and exploit the nonlinearity that happens when they vibrate at large

Allen strikes a traditional East Asian gong in his lab and uses a laser to precisely measure the nonlinear vibrations associated with the multiple tones. He is working to compare those measurements with computer models in hopes that one day he'll be able to account for nonlinear vibrations like these. The ability to properly account for nonlinearity would be useful for all sorts of industries.

amplitude to pump the vibration into high frequencies where it is more quickly dissipated. This is similar to how a gong pumps vibration to high frequencies when struck hard," Allen says. "In the past, engineers have always designed aircraft and spacecraft so that the vibration stays linear because that is all that current computer models can reliably predict."

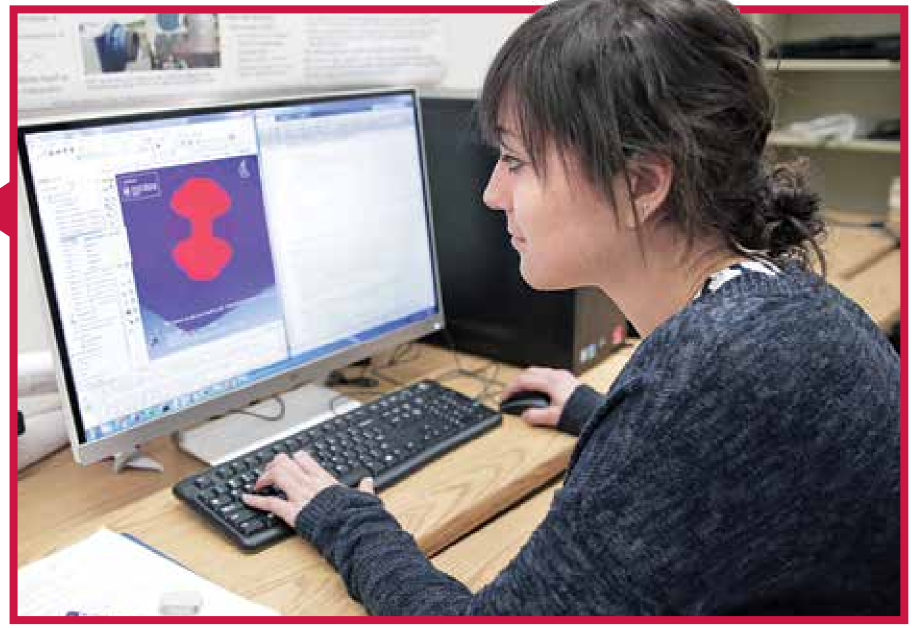
But from a design aspect, nonlinear structures are superior, Allen says—or, they would be if humans were able to use nonlinearity properly.

"For instance, humans are nonlinear," Allen says. "Your muscles, tendons and joints all behave nonlinearly. It makes us more resilient and tougher, so we can survive impacts and vibration. In contrast, a highly linear structure like a crystal glass responds dramatically to vibration at the right frequencies, shattering when the stresses become large enough."

The ability to properly account for nonlinearity would be useful for all sorts of industries, not just advanced aircraft. As a result, Allen's lab is full of machines that companies have donated to see if Allen's group can test or model them.

MORE: go.wisc.edu/matt-allen-nonlinear

UNDERGRADUATE FELLOWSHIP HELPS STUDENT PURSUE HER GOALS



Emily Jewell models a bolted joint.

Photos: Stephanie Precourt

Bolts hold many aspects of our world together; without them, that world would fall apart. And Emily Jewell, who is double-majoring in engineering mechanics and math, is doing research to make sure that doesn't happen.

In 2016, Jewell received a Hilldale Fellowship to work on a project involving bolt interfaces with her faculty advisor Matt Allen. Jewell is one of 100 UW-Madison undergrad students with independent research projects to receive a Hilldale Fellowship in 2016.

The fellowship supports Jewell as she studies the nonlinearities of bolted joints by looking at surface contact and energy dissipation. When a preloaded, tightened bolt joins two components of a structure, the components will slowly slip relative to one another. Jewell studies this slippage at a microscopic level and how it causes energy dissipation known as damping.

There is currently no efficient method for analyzing and modeling damping at bolt joints, and existing methods are computationally and financially expensive. Jewell's work strives to replace current costly analysis methods with a quasi-static method that will quickly and accurately predict the damping at the bolt joint. Still, computationally, her models take a couple of hours to run, so one of the most challenging parts of this work is making sure that the inputs of the model are immaculate before she submits it. "Sometimes you get the results and they just don't make sense," Jewell says. "Then you realize a tiny mistake in the input that has cost you several hours of research."

But the frustration of lost time is part of the learning process that makes the work rewarding in the end. The most rewarding part, Jewell says, is when she submits a clean model and gets results that match up with others' existing theories or experimental data.

Jewell shares these results with collaborators from the Milwaukee School of Engineering and Michigan State University during weekly or bimonthly Skype meetings. Through this collaboration, Jewell gains insights from collaborators and gets to see how research is done at different institutions.

Jewell presented the results of her research at the UW-Madison Undergraduate Research Symposium in May 2017 and also at an ASME conference. She views the Hilldale fellowship as one step on a path to future scholarship: The fellowship helped her earn a prestigious 2017 Goldwater Scholarship and lays the foundation for her goal of a PhD in aerospace engineering.

"It's a gateway for my future," she says.

RETIRED PROFESSOR USES ENGINEERING EXPERTISE TO SOLVE

ARCHAEOLOGICAL MYSTERIES

When NASCAR driver Kyle Busch suffered a race-ending crash while leading the Daytona 500 in February 2017, he wasted no time casting blame on Goodyear, the tire manufacturer and official provider of NASCAR's highly engineered and specialized tires.

Race car crashes can result from almost any problem, but the Kyle Busch-Goodyear episode reflects the make-it-or-break-it status of tires in car racing. Race car tires are some of the most precisely engineered hunks of rubber and metal in existence.

It should come as no surprise, then, that tires were of similar importance to Kyle Busch's ancient equivalents in the world of Roman chariot racing.

And yet, it took a retired engineering professor studying a toy model pulled from the Tiber River to establish that the ancient Roman chariot racers were as fixated with the performance of their tires 2,000 years ago as Kyle Busch is with Goodyear's tires today.

Professor Emeritus Bela Sandor retired from decades of teaching and research at UW-Madison in 1997. In the two decades since, Sandor has turned his longtime interest in ancient chariots into a robust line of academic inquiry, bringing engineering expertise to the inexact science of archaeology.

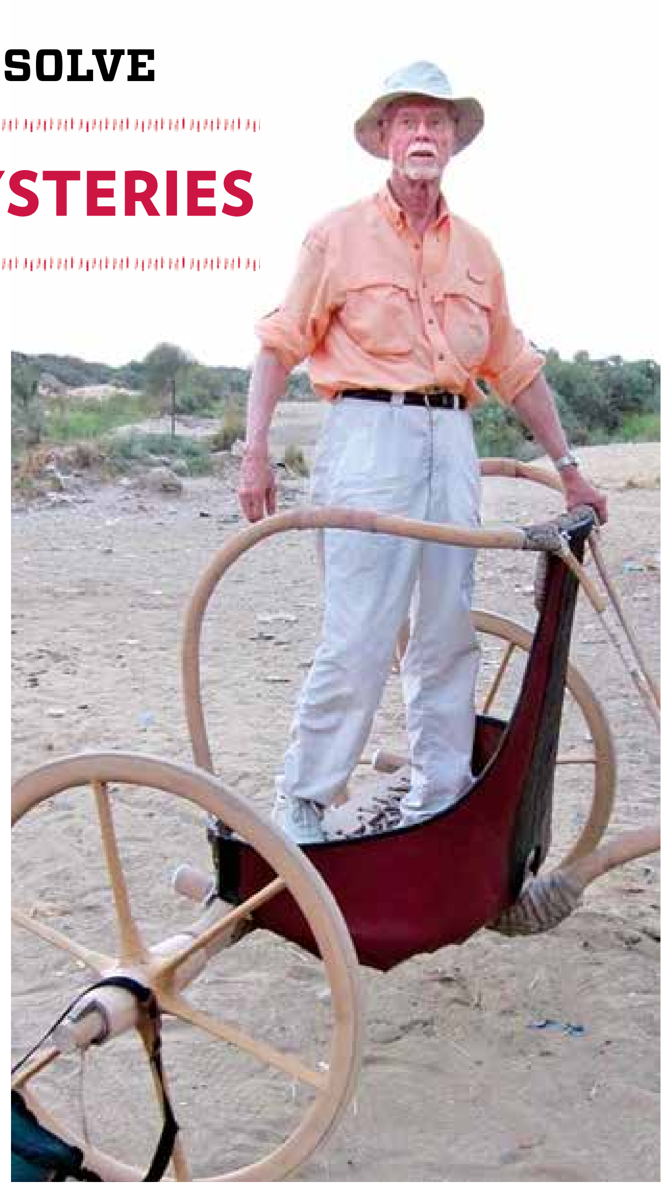
Sandor wants to understand how the two-wheeled vehicles ubiquitous in the ancient world were engineered. Over the years, he has been building the case that the ancients were far more technically sophisticated in their chariot design than modern archaeology scholars have often given them credit for. But a dearth of physical specimens means Sandor has had to get creative in his sleuthing.

"Of all the chariots that have been used in history—there have been literally millions—there are very few in existence today. And there's not a single Roman racing chariot left in existence," Sandor says.

So what is an archaeo-engineer to do? Like most archaeologists, Sandor has depended on art to illuminate the ancient world. Thousands of paintings and mosaics survive that richly—and in large part accurately—depict the Romans' obsession with chariot racing, complete with depictions of catastrophic crashes. It was these crashes—often shown as occurring on the oblong Roman racetracks' tight corners—that particularly interested Sandor.

While at UW-Madison, Sandor taught fundamental engineering courses, including statics and dynamics, and his expertise is in fatigue and fracture. He knew that Roman chariot teams, just like modern drivers, would deal with two competing aims—speed and safety. The aim for speed was aided by a lightweight vehicle, which would mean an easier load for the horses. But lightweight construction included all parts of the chariots, including the wheels. And a lightweight wheel could also prove to be a weak spot.

Those weak spots often led to catastrophic crashes, which were more likely to occur around the track's tight corners, where the speeding chariots would lurch rightward as the horse-drawn vehicles turned sharply left. Sandor was sure that ancient Roman chariot racers were acutely aware of, and would have wanted to brace for, sharp



Photos courtesy of Bela Sandor

Bela Sandor assesses a model of a "Tut class" Egyptian chariot built for a PBS Nova special. The special, which sought to understand how the ancient Egyptians developed chariots into superior war machines, depended in large part on Sandor's analyses of chariots discovered in King Tutankhamun's tomb. Sandor's latest ancient chariot discoveries have focused on Roman racing chariots.

turns in the track. But the Romans' frescos, detailed as they are, did not on their own reveal what, if any, features the Romans built into their racing chariots to brace against this stress to the right wheel.

Enter the toy model. Keen on learning anything he could about how the Romans optimized their racing chariots, Sandor traveled to the British Museum in London. He was interested in an item of little stature—a small bronze toy. Sandor calls it the "Tiber model" because it was discovered in Rome's Tiber River in the 19th century. It's believed to have been cast in the 1st or 2nd century CE, and it's a remarkably detailed and seemingly accurate model, Sandor says. Even though it is literally a toy, the model is the best three-dimensional depiction of a Roman racing chariot known to scholars.

That's why a curious feature Sandor noticed while examining the model is so intriguing. A small ridge encircles the rim of the right wheel. Crucially, the ridge is present only on the right wheel—the left wheel's rim is smooth. Sandor believes the right wheel's ridge is possible evidence that at least some Romans engineered their chariots to compensate for the large stresses acting on the right wheels. He believes the ridge represents an iron tire, which bolstered the right wheel to withstand the hard left turns.

Drivers were faced with a few options, Sandor believes: Fit iron tires onto both wheels, the right wheel only or neither wheel. Iron tires, while reinforcing the wheels, would weigh them down. The tires would also alter the wheel's distribution of mass in a disadvantageous way, slowing their acceleration potential by increasing their rotational inertia. Sandor believes the Romans understood these concepts, and that many chariot racing teams would strike a balance between performance and safety.

"If I were in their shoes, what would I do?" Sandor asks. "Do I want to average my luck and do something that helps me win, say, two out of three races?" That "something" would be fitting an iron tire on the right wheel only.

Modern race car engineering also often features vehicles designed with bolstered right sides as most car races—like the ancient Roman chariot contests—run counterclockwise around a track.

Sandor's Tiber model findings were published in the paper, "Tire choices in Roman chariot racing," which appeared in the Oct. 31, 2016, issue of the *Journal of Roman Archaeology*.

Sandor's examination of this bronze toy chariot, cast in the 1st or 2nd century CE, revealed a small ridge on its right wheel, which Sandor believes represents an iron tire.

The small ridge that Sandor believes to represent an iron tire is plainly visible in this image. Sandor believes that many Roman chariot racers would have outfitted only their right wheels with iron tires, in an effort to balance speed and safety. The chariot is housed at the British Museum in London.

The Tiber model's left wheel is smooth, which Sandor believes is a deliberate representation of a wheel without an iron tire. Iron tires would slow the chariots by adding weight and reducing the speed of acceleration, and there would have been less reason to bolster the left wheel on a counterclockwise track.

TODD ALLEN to lead Grainger Institute for Engineering energy thrust

Given the great scope and complexity of the energy challenges facing society, innovative research collaborations across disciplines hold the most potential to produce transformative technological breakthroughs.

Through the Grainger Institute for Engineering, an incubator for transdisciplinary research in the College of Engineering, the college is poised to drive advances that help solve technological challenges in several areas, including energy and sustainability, which is the newest focus area in the institute.

Todd Allen, previously a senior visiting fellow at the policy think tank Third Way, has returned to UW-Madison to lead the energy and sustainability thrust area in the Grainger Institute for Engineering.

Allen served as a faculty member in the engineering physics department for 10 years before taking a leave of absence in 2013 to serve as deputy director of science and technology at the Idaho National Laboratory.

"I'm excited to return to UW-Madison in this new role as thrust lead in the institute," Allen says. "It's a great opportunity to create some new, innovative approaches to cross-disciplinary research collaboration and education at the university, which will enable us to make a greater impact on energy issues."

While working at Idaho National Laboratory, Allen was in charge of overseeing all energy and national security research at the lab, and he focused on bringing together researchers from disparate groups for fruitful collaborations.

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For example, Allen points to a successful collaboration between a staff member in the lab's national security group and researchers working on nuclear fuel issues. The staff member was working on harnessing advanced digital image processing to identify subtle changes in an image that might indicate a security threat. On the nuclear fuel side, researchers want to ensure the fuel maintains its integrity and doesn't crack or leak, so they conduct visual exams to see if cracks might be forming.

"It's a big national lab, and the nuclear fuel people had never met the national security people," Allen says. "But once you figure out how to connect these different researchers, they really wanted to work together because the nuclear researchers saw how they could improve their ability to understand what was going on in the fuel by connecting to the technology that the nuclear security staff member was working on for a totally different reason."

Similarly, Allen aims to create opportunities to bring together UW-Madison faculty members from various disciplines to tackle big energy challenges in new ways. "The significant energy and sustainability challenges are bigger than a typical single faculty member's group, which tends to focus deeply on certain technical areas," Allen says. "With the Grainger Institute for Engineering thrust, the idea is to figure out clever combinations of people's skills in order to address these big energy problems."

In this new role, Allen will lead the development of large-scale multidisciplinary programs in the area of energy and sustainability. Allen's background is in nuclear engineering, and in addition to his responsibilities as a thrust lead in the institute he will rejoin the engineering physics faculty and run his own research group.

Beyond developing large-scale research programs that help solve critical technological challenges, Allen ultimately wants the cutting-edge work at UW-Madison to help influence national energy policy.

"I want to help make better connectivity between the faculty members and the work they're doing at UW-Madison and the people in policy space, so our work can have an even greater positive impact on society," he says.