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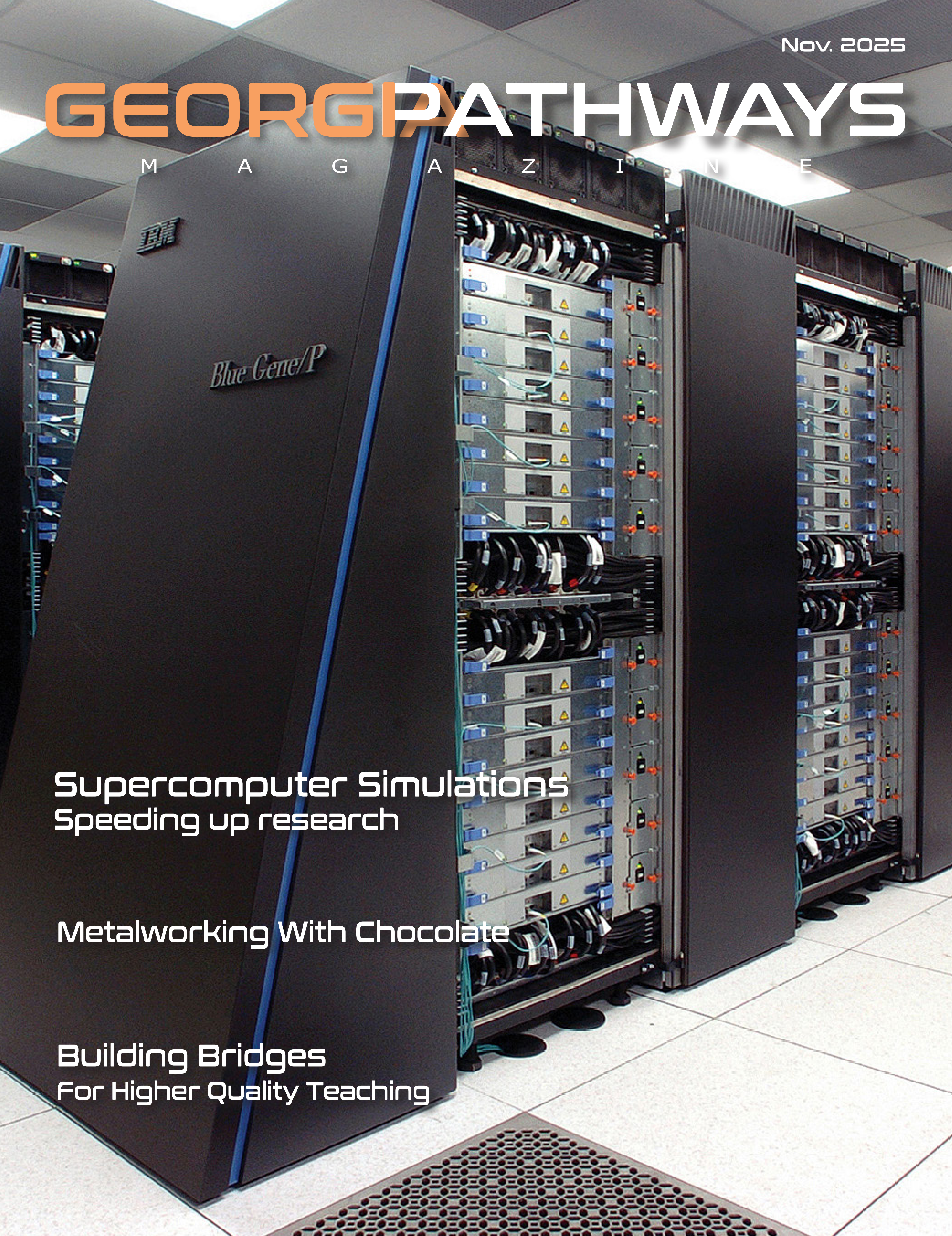
GEORGIA PATHWAYS

MAGAZINE



Supercomputer Simulations
Speeding up research

Metalworking With Chocolate

Building Bridges
For Higher Quality Teaching

The Technology Association of Georgia Education Collaborative (TAG-Ed) strengthens the future workforce by providing students with relevant, hands-on STEM learning opportunities and connecting them to Technology Association of Georgia (TAG) resources.

Formerly the TAG Foundation, TAG-Ed is a 501(C)(3) non-profit organization formed by TAG in 2002. Later, the organization's name was re-branded to TAG Education Collaborative to facilitate our role as the leaders for K-12 STEM education in Georgia.

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Welcome to the November 2025 edition of Georgia Pathways Magazine, your monthly look into the people, ideas, and technologies haping Georgia's innovation economy. As industries evolve and new opportunities emerge, one constant remains clear: the need for forward-thinking talent that is ready to lead in science, technology, engineering, and beyond.

This month, we'll examine some of the exciting frontiers of tech and the developments that directly affect Georgians, as well as the STEM education initiatives that are building bridges towards a future of continued technological innovation. In "Supercomputers Speed Up Chemical Reactions," we get an exciting report on the ability of AI-assisted simulations to rapidly advance chemical research.

"When STEM isn't STEM" then helps us understand the changing STEM landscape, while "Metal Working with Chocolate" highlights an initiative for candy lovers that introduces welding and machine skills. By highlighting biological advancements, "Welcome to the Mitoverse" examines the role of mitochondria research in driving innovation and better outcomes in medicine. "Building STEM Bridges" will update us on the educator coaching initiatives that are developing and improving STEM education.

Georgia's STEM education outcomes are crucial for both producing the next innovative generation of leaders and ensuring that Georgia's students have a competitive edge for their futures. That's why TAG Education Collaborative
is holding Georgia's Day of Code on December 5, 2025, a virtual event that provides coding and AI training to students free of charge. During the event, students of all ages will participate in Python coding workshops, AI training, and community engagement activities with Georgia's Department of Education.

This program will be crucial in providing no-cost education to the next generation of tech leaders in Georgia and beyond. Read more about Georgia's Day of Code, registration instructions, and sponsorship opportunities: https://tagedonline.org/georgia-day-of-code/

Larry K. Williams
President
TAG / TAG-Ed

Larry K. Williams serves as the President and CEO of the TAG and the TAG Education Collaborative. TAG-Ed's mission is to strengthen Georgia's future workforce by providing students with relevant, hands-on STEM learning opportunities by connecting Technology Association of Georgia (TAG) resources with leading STEM education initiatives.

Supercomputer simulations show how to speed up chemical reaction rates

By Coury Turczyn / ORNL

Using the now-decommissioned Summit supercomputer, researchers at the Department of Energy's Oak Ridge National Laboratory ran the largest and most accurate molecular dynamics simulations yet of the interface between water and air during a chemical reaction. The simulations have uncovered how water controls such chemical reactions by dynamically coupling with the molecules involved in the process.

This new understanding of water's role could help researchers develop methods to accelerate chemical reactions at the interface, potentially increasing their efficiency and productivity for industrial processes. Specifically, the team from ORNL's Chemical Sciences Division investigated a bimolecular nucleophilic substitution reaction, known as SN2. SN2 is one of the most common mechanisms in chemical, physical, biological and atmospheric chemistry. For example, SN2 reactions are vital in drug synthesis and were once used in the production of ibuprofen.

"This is the first paper that answers the question – 'What is the dynamic role of the air-water interface in modulating the reaction rate of chemical reactions?'" said Vyacheslav Bryantsev, leader of ORNL's Chemical Separations group and co-author of the study, which was published in the Journal of the American Chemical Society. "We confirm in this study that the overall reaction rate at the air-water interface becomes faster compared to the reaction rate in the main environment of water alone."

The team's simulations indicate that chemical reactions involving water and air could be sped up by drawing the interacting molecules out of the water's bulk environment (meaning, deep into the water, away from the interface) and closer to its surface, where air and water interact. This results in a reduction of water's dynamic coupling with those molecules, allowing the chemical reaction to proceed with less interference.

It is expected that water should influence the reactions rate since it mediates the reaction—however, to what extent and how water controls the reaction were unknown.

"We found that the more the water molecules couple, the more they hinder the reactions. If we can reduce that dynamic coupling, we'll have a faster reaction rate," said Santanu Roy, a scientist in ORNL's Carbon and Composites group and co-author of the study.

"Our study suggests that if we can control that coupling by changing the environment at the interface – how water affects the reactions – then we should be able to control the reaction rate."

Based on previous experimental work that showed that positively charged surfactant molecules will attract negatively charged amino acids, the researchers simulated such a surfactant to draw more amino acids into the interface and confirmed an increased reaction rate of 10% to 15%. The ORNL team's study showed that as a gas reacts with amino acids, it goes through repeated dynamic coupling cycles with the water molecules, slowing down the chemical reaction before finally resolving into a new product.

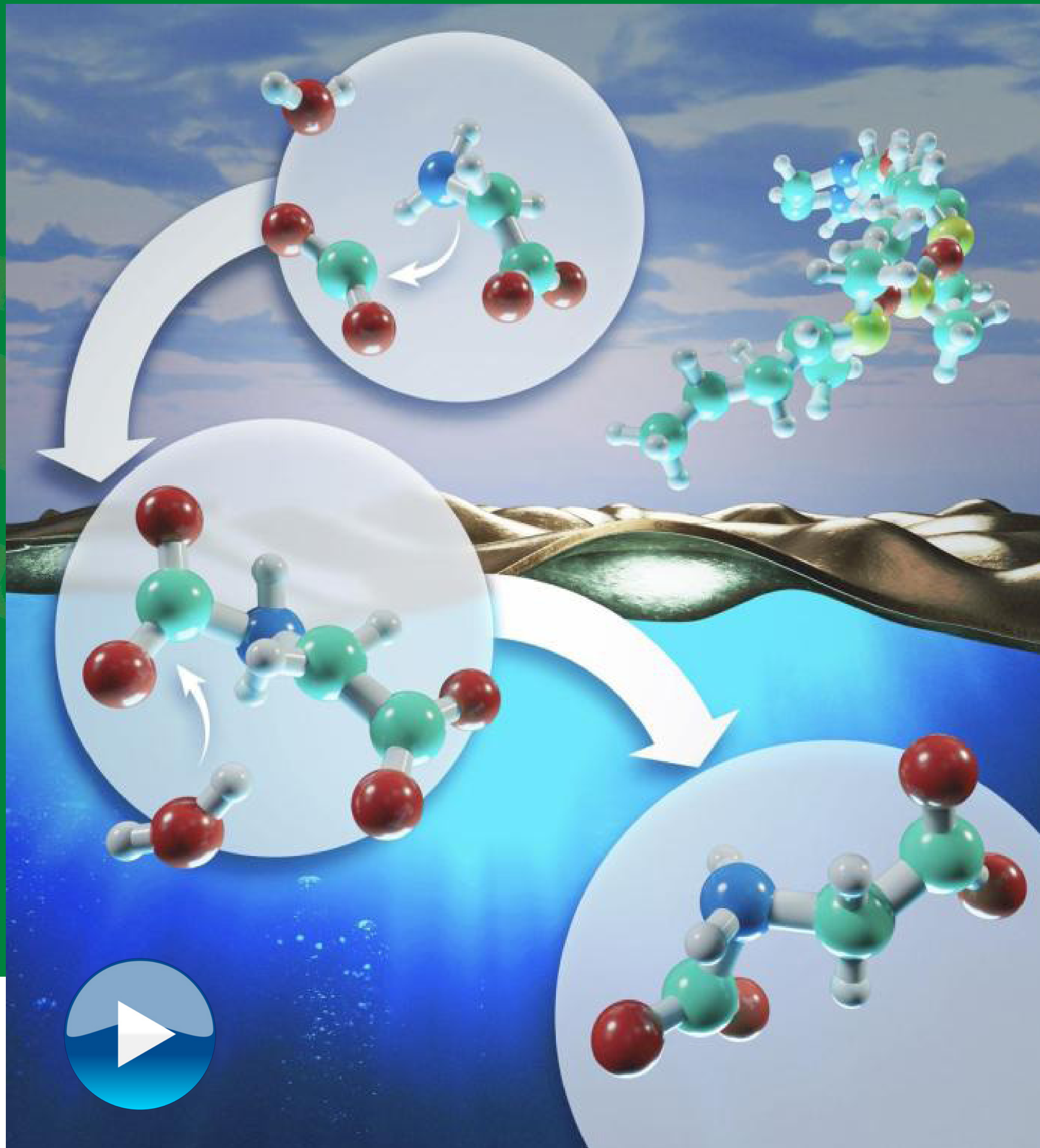
"Our theories would not have been possible to validate or investigate if we didn't have leadership computing power."

- Santanu Roy, R&D staff in the Chemical Sciences Division at ORNL

Using the open-source CP2K code, the ORNL team modeled the reaction trajectories of the molecules on the Summit supercomputer. They then conducted a kinetic analysis of these paths to form an energy profile of the process.

"Our theories would not have been possible to validate or investigate if we didn't have leadership computing power," Roy said. "We needed to run thousands of trajectories – for every point in that energy profile. We had to run a lot of simulations at the electronic level, which takes a lot of time, and we had to run all of those in parallel. Without Summit, it's really impossible to do."

"The challenge here was to actually understand the role of water and how it controls the reaction rates and their pathways – the mechanism. To do that, we really had to understand the reaction path. This is where Summit came in, and it helped us a lot."



At the air-water interface, a negatively charged amino acid carries out a nucleophile attack on a gas molecule to convert it into a product. The reaction rate is enhanced due to significant reduction in the dynamical coupling of the solvent water with the reaction paths at the interface. Credit: Adam Malin, ORNL, U.S. Dept. of Energy

Summit was managed by the Oak Ridge Leadership Computing Facility, a DOE Office of Science user facility located at ORNL. The OLCF offers leadership-class computing resources to researchers from government, academia, and industry who have many of the largest computing problems in science. This project was supported by the SummitPLUS program, which allocated computing time on Summit in its last, extended year of service in 2024.

UT-Battelle manages ORNL for DOE's Office of Science, the single largest supporter of basic research in the physical sciences in the United States. DOE's Office of Science is working to address some of the most pressing challenges of our time. For more information, visit energy.gov/science. — Coury Turczyn

When STEM Isn't STEM:
Reimagining Classrooms for the Innovators of Tomorrow

By Shelly A. Muñoz

As the school year begins, classrooms proudly display "STEM" banners, yet too often the essence of STEM, Science, Technology, Engineering, and Mathematics, remains missing. Students may be counting, coding, or following instructions, but the heart of STEM, curiosity, innovation, and problem-solving, is often absent. Are we truly preparing students for the challenges of the 21st century, or are we just labeling classrooms without changing learning experiences?

Even when classrooms carry the STEM label, key elements are often missing. Science, technology, engineering, and math are frequently taught separately, keeping students from seeing how these areas connect to real-world problems. Traditional teaching methods often focus on memorization rather than exploration, leaving little room for students to ask questions, investigate, or create.

Without meaningful problems, learning can feel empty, and students may struggle to apply knowledge in ways that build engagement and critical thinking.

The difference is clear when students take part in authentic, hands-on STEM activities. In a fifth -grade classroom, students design 3D-printed fishing lures, calculate density, test buoyancy, and refine their designs based on results. Physics, math, and engineering come alive, giving students a real connection to STEM concepts. Middle school students address local water quality issues by collecting samples, analyzing data, and proposing solutions to reduce pollution. High school robotics teams competing nationally show another side of STEM.

Students learn teamwork, resilience, and problem-solving as they iterate on their designs. In all these cases, students tackle real challenges while building communication and leadership skills.

To bridge the gap between STEM labels and real learning, educators can try several strategies. Integrate STEM subjects so students see how what they are learning applies in the real world. Shift to student-driven inquiry, letting students ask questions, explore, and figure things out themselves. Use project-based learning to address real problems, and encourage teamwork, discussion, and presentations. Celebrate experimentation and resilience so students see challenges as opportunities rather than setbacks.

Transforming STEM classrooms takes effort. Professional development helps teachers design interdisciplinary, hands-on learning. Curriculum redesign should focus on projects and real-world problems. Partnerships with local businesses and organizations give students authentic experiences and mentorship. Above all, classrooms need to be student-centered spaces where curiosity and collaboration thrive.

This year, let us commit to more than just labeling classrooms as STEM. Let us create places where students are actively solving problems, innovating, and building skills for a rapidly changing world. As I often say, "STEM education is not about teaching students to follow directions. It is about giving them the tools, curiosity, and confidence to explore, create, and solve the problems of tomorrow."

Expanding Learning Beyond the Classroom

A strong STEM education goes beyond the school day. Every community, regardless of neighborhood, provider, or economic status, deserves high-quality out-of-school programs that meet students' needs. Providers can focus on offering a wide variety of enrichment opportunities, including STEM, arts, and athletics. Collaborations among

schools, cities, and community organizations strengthen programs. Families need clear information about program options, and ongoing data collection helps improve attendance, satisfaction, and outcomes.

Sustaining STEM Amid Budget Cuts
Maintaining high-quality STEM programs when budgets are tight is challenging, but possible. Schools can focus on the strategies that have the biggest impact on learning and engagement. Partnerships, grants, and volunteers can help provide hands-on experiences even with limited funds. Thoughtful curriculum design ensures every activity is purposeful, connecting classroom lessons to the real world. Protecting the quality of STEM programs requires careful spending, creativity, and a commitment to students.

Conclusion

STEM education is not about following directions or checking boxes. It is about curiosity, creativity, and taking risks. When students engage in hands-on, real-world problem solving, they become innovators, problem-solvers, and leaders. Every student deserves the chance to explore, experiment, and grow the skills and confidence to thrive. By making STEM meaningful, we give the next generation the tools to not just face the future, but to shape it.

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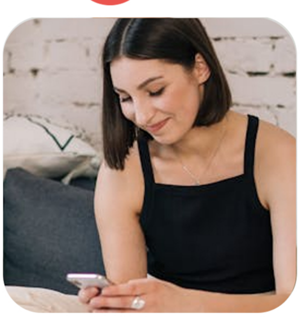

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Metalworking with *Chocolate*

By Samantha R. Trzinski

Students tend to be the most invested in lessons being presented to them when given the opportunity to participate in hands-on activities. Detailed lectures on metalworking may bore students and make them less interested in manufacturing career pathways. In contrast, activities in which students learn metalworking processes promote student interest and encourage future learning.

One of the easiest and tastiest ways for students to learn about metalworking is with chocolate. Metals can be expensive, and shaping, forging, and joining them can be dangerous and require large equipment that is difficult to maintain in a classroom setting. Using chocolate as an analog for metal is an effective way to spark interest and demonstrate to students just how fun metalworking and manufacturing can be.

This article outlines the ways in which chocolate can be used to teach welding, forging, and casting in K-12 classrooms and asserts the importance of developing and implementing similar activities to encourage students to pursue STEM fields rooted in metallurgy and manufacturing.

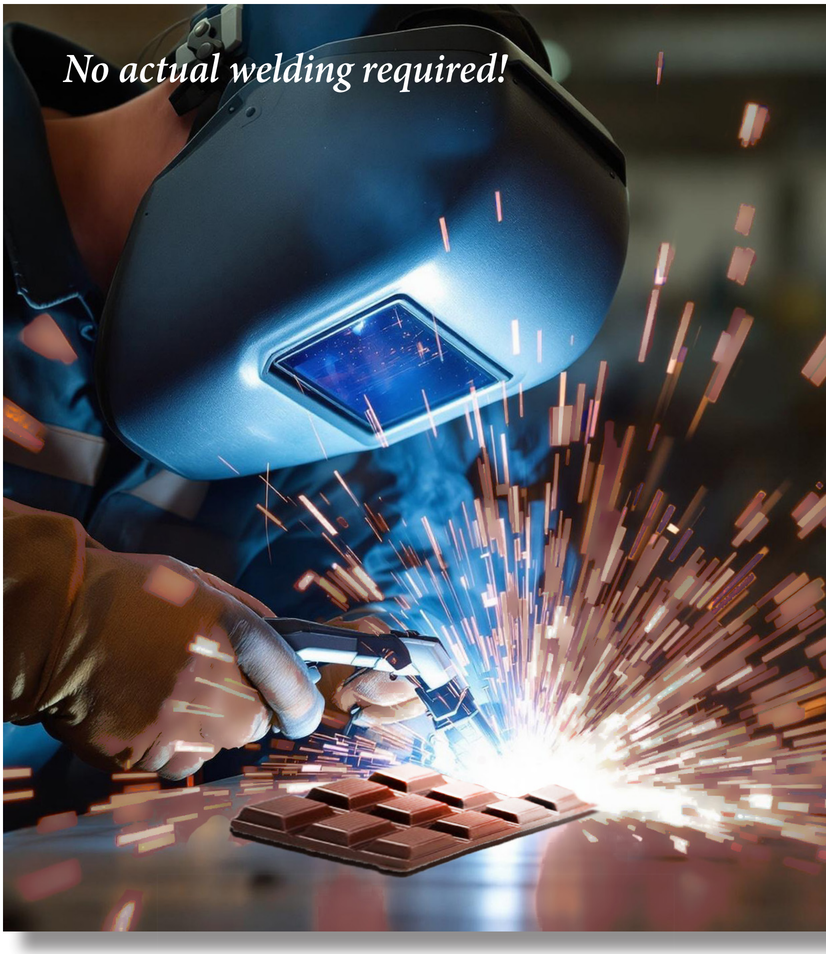
Welding Chocolate Bars

Students can learn about various welding processes by using chocolate bars and low-temperature heat sources. Welding is a common type of metalworking and is used to connect pieces of metal together. Typical welding requires tremendous levels of heat and energy to melt and fuse metal together, making it ill-suited for the classroom and dangerous for younger students. In contrast, chocolate welding requires much lower levels of heat that can be achieved in a classroom setting with low risk.

For this activity, students should be provided with two chocolate bars that they need to connect. The way in which they connect their chocolate bars will depend on the age of the student. For elementary-aged students, chocolate should be melted ahead of time and put into a pastry bag so that they can pipe a line of melted chocolate where their two chocolate bars meet. Middle to high-school-aged students can use a heat source like a soldering iron to melt their chocolate bars where they meet to weld them together.

For an additional challenge, students can be given different types of chocolate (white, milk, and dark) to see how they behave differently when melted. Since each of these types of chocolate have different melting points, the welds will be sturdier or weaker depending on the chocolate used.

This approach to teaching welding is rudimentary, but it opens the door to encourage students to learn more about welding in the future. Students who practice welding with chocolate will be well-prepared to learn about various welding approaches when they are older because they will have necessary foundational knowledge on which they can build.



Forging with Modeling Chocolate

While typical chocolate bars are ill-suited for forging because they shatter upon being hit with a hammer or melt easily when heat is applied, modeling chocolate is an effective medium to use when teaching about metal forming.

Modeling chocolate has a similar consistency to clay or other modeling doughs -- it is pliable and can be stretched, pulled, and squished with relative ease.

Metal, when properly heated to high temperatures, has a similar consistency to this modeling clay, which makes it an optimal analog to use in a classroom setting where furnaces, hammers, anvils, and presses are unavailable.

Students should be provided with modeling chocolate, scissors, rollers, and molds for this activity. Though the first image that comes to students' heads when they think of forging may be that of a medieval blacksmith, forging continues to be an important metal forming process through the current day and requires myriad tools like rollers, extruders, shears, and dies to create target shapes. For this activity, students should attempt to create a specific shape using their modeling chocolate and utilize the tools that they are given to simplify the task.

Casting Chocolate Shapes

Chocolate casting is a simple activity that gives students the chance to learn about crystalline structures and physical state changes. In traditional casting, metal must be heated to its critical point and melt into a liquid state. The liquid metal is then poured into a mold made of materials like ceramic or sand.

Once the metal cools, the shape is then removed from mold and may be machined afterward for a smoother finish. While tin castings can usually be done in a K-12 classroom because of the low levels of heat needed in comparison to other metals like steel or iron, metal casting can be a costly activity that is unsafe or difficult for younger students to do.

Chocolate casting works in a similar way but uses chocolate in place of metal. Chocolate melts into its liquid state at temperatures as low as 82 degrees Fahrenheit. However, before casting, chocolate will need to be melted to a higher temperature (120-130 degrees Fahrenheit) to temper it and optimize its crystalline structure. As the chocolate melts, students can learn about physical state changes. By having some chocolate melt and resolidify at lower temperatures, students can also see the differences between crystalline and non-crystalline structures. The tempered, crystalline-structured chocolate will be smooth and shiny and will break cleanly with a solid snap. In contrast, the untempered chocolate that lacks the same crystalline structure and was heated to a lower temperature will be duller, grainy, and more likely to bend. With supervision and guidance from a teacher, students of all ages can cast chocolate into molds of their choice. More advanced students can also make their own "sand" molds using brown sugar that they compress in a bowl and make the shape that they wish to cast with chocolate.

Why Labs Like This One Matter

Hands-on activities that spark student interest are necessary to build the future metalworking workforce in America. Though manufacturing was once a commonly-pursued career pathway, it has decreased considerably in popularity. It has become something that K-12 students often consider outdated or antiquated in the age of robotics, artificial intelligence, and other advanced technologies. However, manufacturing is alive and well around the world, and recent pushes have aimed to revitalize the industry in America.

This chocolate-based lab is a way in which teachers can incorporate metalworking and manufacturing into their classrooms to build interest in students of age levels.

As students become older and their interest in these industries grow with the support of teachers, students may investigate the various manufacturing career pathways that exist and see that metalworking is not as old-fashioned as they previously thought. The images of the medieval blacksmith and grimy factories do not accurately depict metalworking in the current day. Modern technology, including robotics, sensors, and artificial intelligence, is a part of twenty-first-century manufacturing.

K-12 students' understanding of manufacturing will not change overnight, though. It is essential that fun, enjoyable, and informative activities that teach metalworking processes be incorporated into classrooms of all levels to build student interest and help guide them toward manufacturing career pathways.

Conclusion

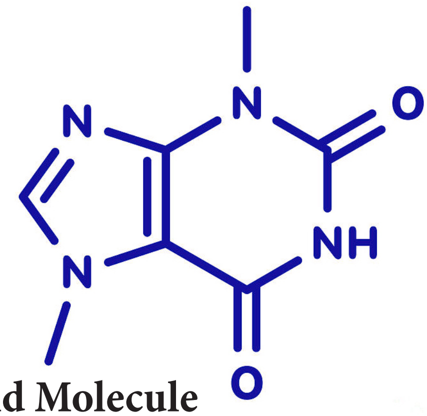
A chocolate-based lab is an effective and inexpensive way to teach K-12 students about metalworking processes. With this lab, students can cast, weld, and even forge with different forms of chocolate and learn foundational materials science information on crystalline structures and physical state changes.

This work with chocolate allows students to learn essential metalworking processes in a safe, low-cost, and delicious way, making it suitable for students and teachers of all ages. Though this lab may only take a single day, it is an example of the type of interactive lessons that need to be incorporated into K-12 classrooms to encourage students to pursue STEM fields like materials science, metallurgy, and advanced manufacturing.

Acknowledgement

The author would like to acknowledge support from the U.S. National Science Foundation Engineering Research Center for Hybrid Autonomous Manufacturing Moving from Evolution to Revolution (ERC-HAMMER) under Award Number EEC-2133630.

Chocolate is a food made from roasted and ground cocoa beans that can be a liquid, solid, or paste, either by itself or to flavor other foods. Cocoa beans are the processed seeds of the cacao tree (***Theobroma cacao)***.



Theobromine Chocolate Alkaloid Molecule

About the author:

Dr. Samantha Trzinski is the Director of Education Outreach and Workforce Development for the U. S. National Science Foundation HAMMER Engineering Research Center. Her current work focuses on building student interest in metalworking and manufacturing and helping support the workforce. She has over a decade of education experience across the country, having taught literature, mathematics, research, and medicine at the K-12, community college, and university level.

Article Audio Version

Building Bridges:

How Administrators and Coaches Can Support High-Quality STEM Teaching

By Shelly A. Muñoz

As STEM education expands in schools, leaders are increasingly asked to observe and evaluate teachers in rapidly evolving fields. From robotics and coding to inquiry-based science and engineering design, effective STEM teaching looks and feels different from traditional instruction. To ensure these classes are evaluated and supported fairly, administrators and instructional coaches must work collaboratively with teachers through intentional coaching cycles, data-informed reflection, and partnership-based principles that elevate practice rather than simply rate performance.

Much of the framework described here is based on Learning Forward's Impact Cycle Toolkit (IC Toolkit) and has been adapted for use in my district. These tools provide a clear, research-based approach to professional learning that aligns beautifully with the inquiry-driven nature of STEM.

Start with Partnership Principles

Before any evaluation or feedback conversation begins, the foundation must be partnership. Jim Knight's Partnership Principles—equality, choice, voice, dialogue, reflection, praxis, and reciprocity—remind us that professional learning is most powerful when it's collaborative, not top-down. Administrators and coaches who approach STEM teachers as thought partners rather than evaluators create a culture of trust. When teachers feel safe to take risks, they are more likely to experiment, reflect, and innovate.
Ask yourself:

- What's working well in your STEM classroom right now?

- What goals would you like to focus on for your next instructional cycle?

These questions shift the tone from compliance to curiosity.

Use Coaching Cycles to Drive Growth

Structured coaching cycles help ensure that professional learning is purposeful and sustained. Each cycle moves through three stages, adapted from the Impact Cycle Toolkit:

Identify – Set a specific goal tied to student outcomes or engagement (for example, “Increase student talk time during collaborative design challenges”).

Learn and Plan – Select a high-impact strategy aligned with that goal, such as explicit modeling, feedback, or retrieval practice.

Implement and Reflect – Collect data, analyze progress, and adjust together.

This cycle mirrors the scientific method—observe, test, analyze, and refine—which makes it particularly resonant in STEM settings. It ensures growth is measurable, not just anecdotal.

Focus on Evidence, Not Opinion

When STEM classes become part of formal evaluation systems, administrators may feel uncertain about what effective STEM teaching looks like. Evidence-based observation focuses on student learning behaviors rather than teacher delivery style.

Look for indicators such as:

- Students engaging in hands-on problem solving and iterative design.
- Evidence of cognitive, behavioral, and emotional engagement—students thinking deeply, collaborating, and showing curiosity.
- Teachers use a balance of content, procedural, and conceptual knowledge to connect theory and practice.
- Intentional use of data, including formative checks, reflections, and student artifacts, to adjust instruction.

Integrate Data Reflection into the Evaluation Process

Gathering and using data shouldn’t be limited to standardized tests. Encourage teachers to bring learning evidence, like exit tickets, design journals, or project rubrics, into coaching and evaluation conversations. Use data reflection protocols that promote curiosity over judgment, for example:

- What does this data suggest about students’ understanding?
- What strategies might strengthen this area next time?

This approach helps administrators model inquiry—the same skill we ask STEM students to develop.

Align Evaluation with High-Impact Practices

To ensure equity and consistency, align observation and feedback tools with high-impact instructional strategies. Practices like explicit instruction, feedback, questioning, collaborative learning, and metacognitive reflection are just as vital in STEM as in other disciplines—they just look different when students are programming robots or testing buoyancy in a 3D-printed boat. Encourage observers to document how students are engaging rather than only noting teacher actions. The goal is to see thinking, collaboration, and problem-solving in action.

Create a Culture of Continuous Improvement

Supporting STEM teachers means creating an environment where experimentation is encouraged, mistakes are viewed as data, and reflection is routine. The Impact Cycle—plan, implement, collect evidence, and reflect—offers a practical framework that mirrors the engineering design process. When administrators and coaches model the same iterative mindset we hope to see in students, we cultivate a school culture where everyone learns through curiosity, evidence, and reflection.

Enhance STEM Pedagogy in Practice

Strong STEM pedagogy is grounded in evidence-based practices that make learning meaningful, rigorous, and engaging:

- The 5E Learning Cycle (Engage, Explore, Explain, Elaborate, Evaluate): Lessons begin with a phenomenon, include investigation, and culminate in student explanation and application.
- Engineering Design Process: Ask, Imagine, Plan, Create, Test, Improve; mirrors the impact cycle and promotes iteration.
- Integration of the 4Cs: Critical thinking, creativity, collaboration, and communication embedded in each lesson.
- Problem-Based Learning: Lessons connect to authentic, real-world problems relevant to students' lives.
- Data-Driven Reasoning: Students use evidence to make decisions, draw conclusions, and revise designs.
- Computational Thinking: Students break down complex problems, recognize patterns, and create algorithms.
- Culturally and Community-Responsive STEM: Instruction honors diverse knowledge systems, local context, and contributions from historically underrepresented scientists and engineers.
- Reflection and Iteration: Students and teachers analyze what worked, what didn't, and how to improve—modeling a growth mindset and inquiry.

Admin Tip: During observations, ask students, "What problem are you solving?" and look for reasoning, collaboration, and iteration—not just correct answers.

Key Questions for Coaches

- How are students using evidence to guide their thinking?
- Are students engaged cognitively, emotionally, and behaviorally?
- What opportunities do students have to collaborate and iterate on designs?
- How does the teacher connect content, procedure, and conceptual understanding in practice?

Sidebar: STEM Pedagogy Highlights

- Encourage hands-on, iterative problem solving.

- Make learning relevant with real-world challenges.
- Promote collaboration and communication.
- Include culturally responsive and inclusive examples.
- Support reflection and evidence-based reasoning.

This framework, adapted from Learning Forward's Impact Cycle Toolkit, has guided how our district supports educators and integrates STEM instruction into evaluation and professional growth.

By grounding evaluation and support in partnership principles, coaching cycles, evidence-based observation, high-impact practices, and STEM pedagogy, we move beyond observation toward true instructional collaboration. In doing so, we don't just evaluate STEM teachers—we empower them to innovate, reflect, and transform learning for all students.

Shelly A. Muñoz is a STEM educator and instructional leader dedicated to advancing innovative teaching practices in K–12 classrooms. With experience designing and implementing project-based learning, coding, robotics, and 3D design initiatives, she helps teachers integrate research-based strategies that promote critical thinking, collaboration, and real-world problem solving.

Shelly also works closely with administrators and instructional coaches to support evidence-based professional development and coaching cycles, ensuring that STEM education is engaging, equitable, and impactful for all students.

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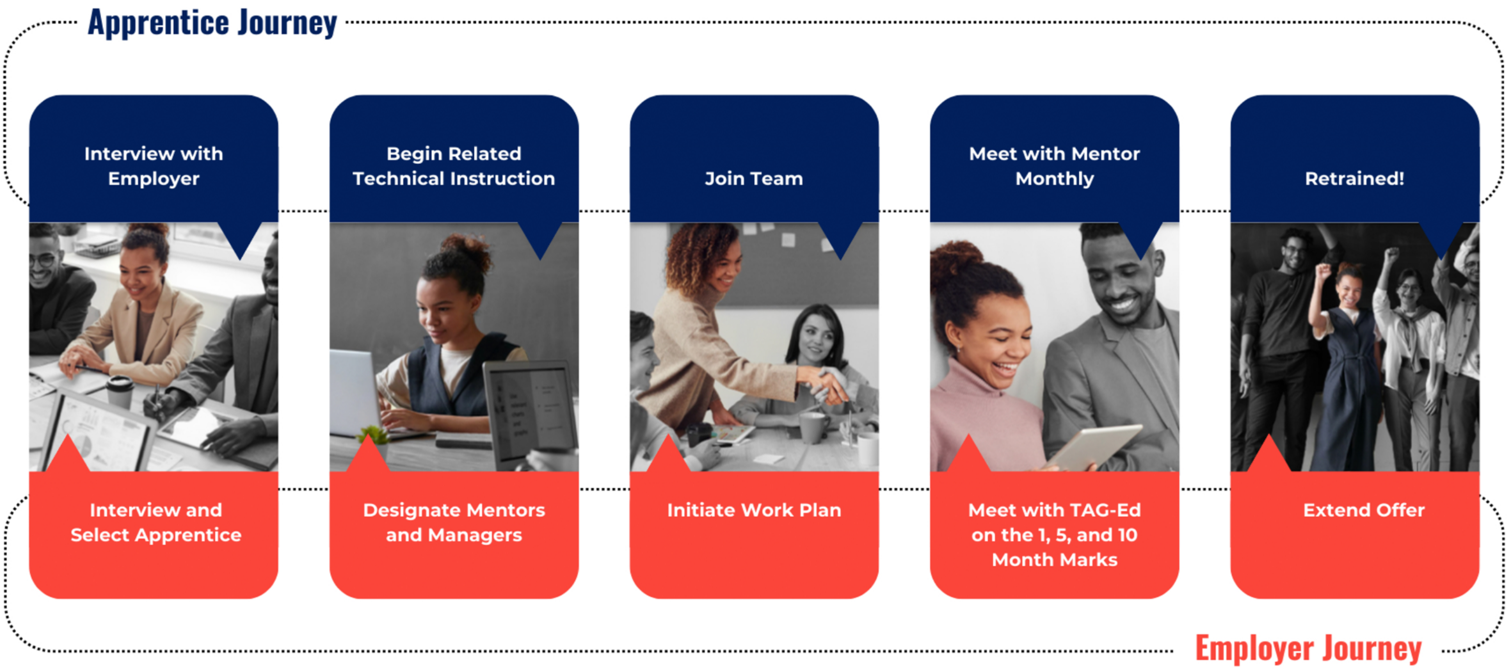

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To understand STEM...

...you must DEFINE STEM. You cannot define an acronym without defining each of the words the letters stand for.

Universities and organizations around the world continue to debate what a STEM career is, but there is no doubt that "every career" uses STEM skills and this observation remains the focus of STEM Magazine.

Science: "The systematic accumulation of knowledge" (all subjects and careers fields)

Technology: "The practical application of science" (all subjects and careers)

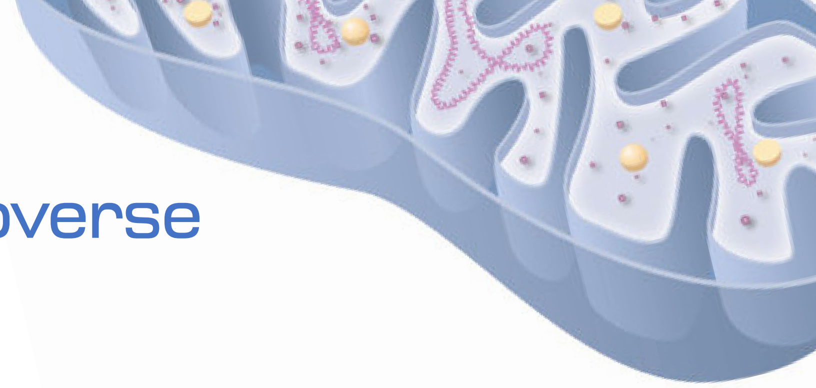
Engineering: "The engineering method: a step by step process of solving problems and making decisions" (every subject and career)

Math: "The science of numbers and their operations, interrelations, combinations, generalizations, and abstractions" (every career will use some form[s])

For a moment, set aside any preconceived notions of what you think a STEM career is and use the above dictionary definitions to determine the skills used in any career field you choose.

These definitions are the "real" meaning of STEM and STEM careers.

MITO WORLD



Welcome to the Mitoverse

By Dane Wolf and Gordon Freedman

Mitochondria are enjoying a moment of renewed attention. They appear frequently in media focused on health, wellness, and peak performance, and they are increasingly the subject of cutting-edge medical research. Yet for most people, the only familiar reference comes from high school biology: mitochondria as the "powerhouses of the cell." While true, that phrase captures only a fragment of their significance. It reduces a complex, dynamic system to a slogan and masks the deeper reality. Mitochondria are central not only to energy production but to nearly every aspect of life, health, and disease.

The story of mitochondria begins nearly 2 billion years ago, when an ancient archaeal cell formed a partnership with oxygen-using bacteria[1]. This merger gave rise to the first eukaryotic cells, the blueprint for all complex life on Earth. Over evolutionary time, the bacterial partners lost most of their genes to the host nucleus. However, they retained a small, specialized genome that continues to power the machinery of energy production[2]. From this symbiosis arose the complexity of multicellular life—plants, animals, and humans alike.

Today, nearly every one of our ~28–37 trillion cells[3] contain mitochondria. Depending on the tissue, a single cell may house hundreds or even thousands, and in some cases, such as the human egg, even 100,000 or more of these organelles[4]. Far from static "beans" submerged in the cytoplasm, mitochondria are constantly moving, dividing, and fusing, responding to the needs of their environment[5]. They not only generate ATP but also regulate signaling, metabolism, cell death, and immunity, roles essential to survival[6].

Despite their centrality, mitochondria have long been underappreciated in medicine. Genetics and the microbiome each had their revolutions; the mitochondrial revolution is coming.

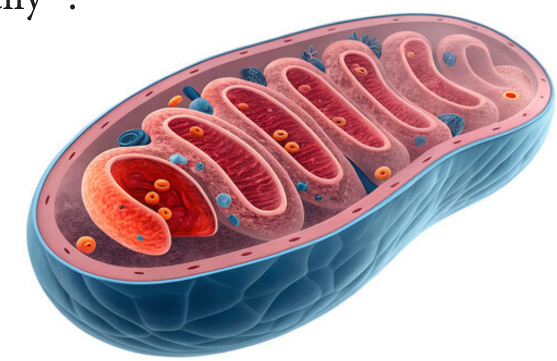
As research continues, they are increasingly being linked to the great health challenges of our time, including cardiovascular disease, diabetes, neurodegeneration, cancer, and aging[7]. Understanding mitochondria more fully will reshape how we think about health, disease, and human potential, a mission at the heart of MitoWorld.

1. What are mitochondria?

All cells depend on a steady supply of molecular energy in the form of adenosine triphosphate (ATP), which powers the countless processes that sustain life. Most of this ATP is made by mitochondria, highly dynamic organelles that typically exist in the hundreds or thousands within each cell. Mitochondria are constantly reshaping themselves through cycles of fusion and division, sometimes appearing elongated, other times punctate. These features are reflected in their name, from the Greek mitos (“thread”) and chondros (“grain”).

Structurally, mitochondria are defined by two membranes. The outer membrane is smooth and relatively porous, but the inner membrane is much less permeable and folded into distinctive crests called cristae[8]. These folds dramatically increase surface area, providing space for the molecular machinery that drives ATP production by harnessing electrochemical gradients[9]. Between the two membranes lies a thin intermembrane space, and inside the inner membrane is the matrix, the central compartment of the organelle.

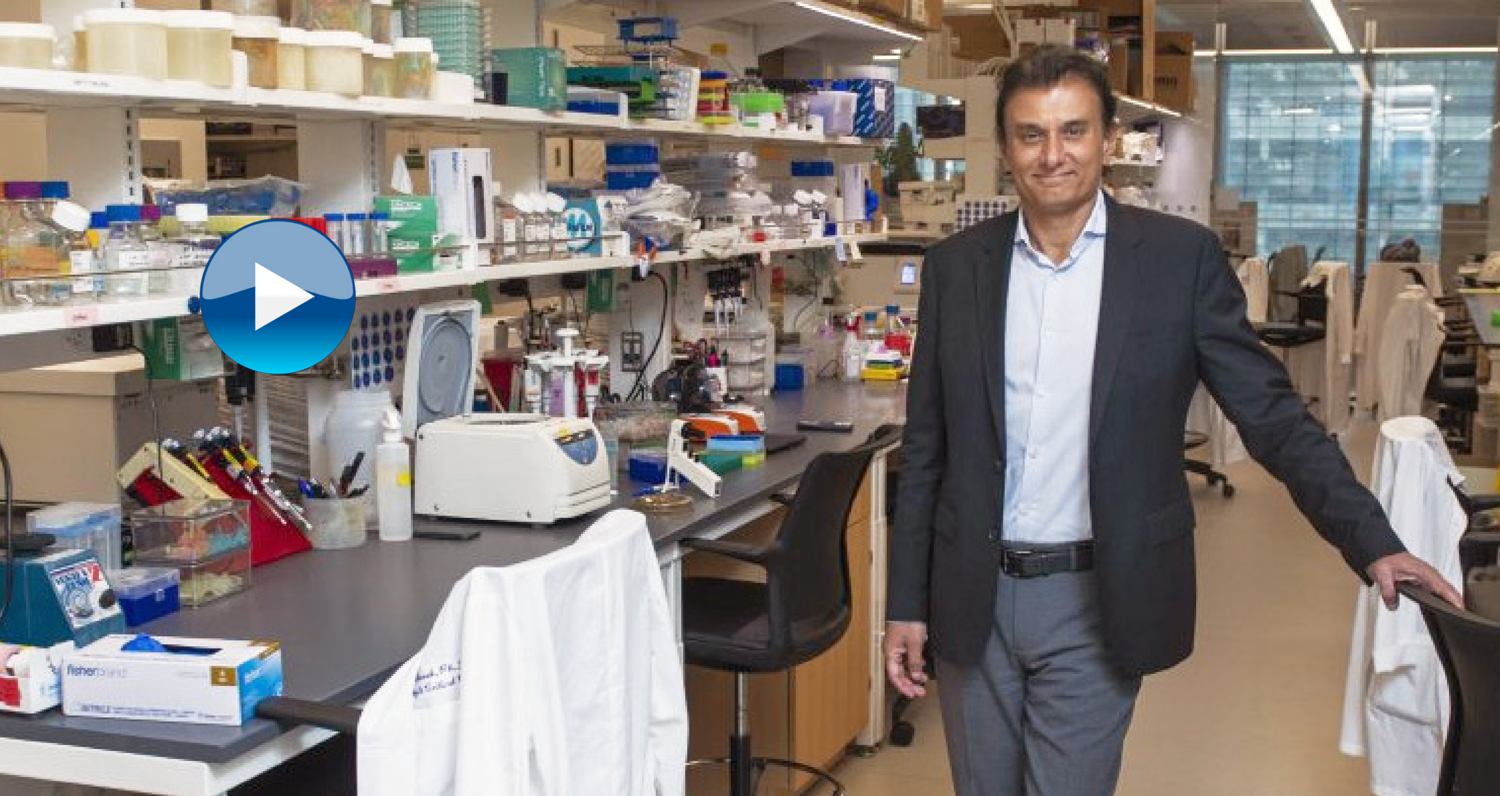
Far from being simple “powerhouses,” mitochondria are complex bioenergetic hubs that harbor over a thousand different proteins[10]. They fuel the cell but also help regulate processes, such as programmed cell death (apoptosis). Remarkably, mitochondria also retain many copies of their own small genome within the matrix. This DNA encodes critical components of the oxidative phosphorylation (OXPHOS) system, along with the genes needed to express them locally[11].



2. Where did they come from?

Mitochondria trace their origins back about 2 billion years to a remarkable evolutionary partnership. At that time, an ancient archaeal cell formed a long-term alliance with a species of α-proteobacteria. These oxygen-using bacteria survived inside the host cell and gradually adapted to life as permanent residents. This merger gave rise to the first eukaryotes, organisms with a nucleus and internal compartments, and it set the stage for all complex life that followed[1].

How this partnership began remains controversial. The classical story suggests that an archaeal host simply engulfed one or more bacteria, which then escaped digestion and multiplied inside. But this explanation, while plausible, lacks direct evidence.



Navdeep Chandel, PhD, David W. Cugell Professor of Medicine, Biochemistry & Molecular Genetics at Northwestern University

A newer model has emerged from the discovery of an archaeon called *Candidatus Prometheoarchaeum syntrophicum*, a microbe that lives today in cooperative partnerships with bacteria[12]. Unlike typical cells, it has unusual long, branching protrusions that seem to wrap around its microbial partners. This finding inspired the "entangle-engulf-endogenize (E3)" model. In this view, early archaea first established close physical contact with bacteria by entangling them. This physical intimacy fostered metabolic cooperation, with each partner providing something the other needed. Over time, the archaeal host fully engulfed the bacteria, which then evolved into the mitochondria found in modern cells.

This extraordinary event—two simple microbes merging to become a single, more complex cell—is now recognized among the most important turning points in the history of life on our planet[13].

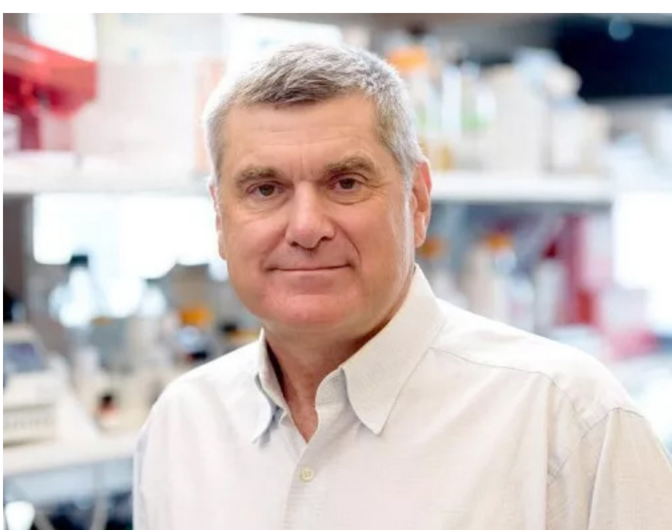
3. How important are they for life?

Mitochondria are indispensable for the existence and evolution of complex, multicellular organisms. While cells can extract a small amount of energy from sugar through glycolysis in the cytosol, mitochondria use oxygen to generate about 15 times more ATP from the same molecule[14]. This leap in efficiency was crucial for the rise of multicellular life, which relies on highly specialized cells with enormous energy demands—most notably, neurons.

Without a steady and abundant supply

of ATP, nerve cells could not maintain the electrical gradients that allow them to send signals, and basic functions such as sensing the world or moving muscles, would collapse. Remarkably, mitochondria make the equivalent of a person's entire body weight in ATP every day, recycling it continuously to keep life going[13].

Energy is only part of the story. Mitochondria are also metabolic hubs that help sustain life in many other ways. They regulate the biosynthesis of essential molecules, such as heme, nucleotides, and steroid hormones, required for maintaining homeostasis from the cellular to the organismal levels[15]. They also act as gatekeepers for processes, such as programmed cell death, ensuring that damaged or dysfunctional cells are safely removed.



Dr. Craig Thompson, MD, President and CEO Sloan Kettering Memorial Cancer Center (SKMCC), 2010-2022, leading SKMCC mitochondrial medicine researcher.

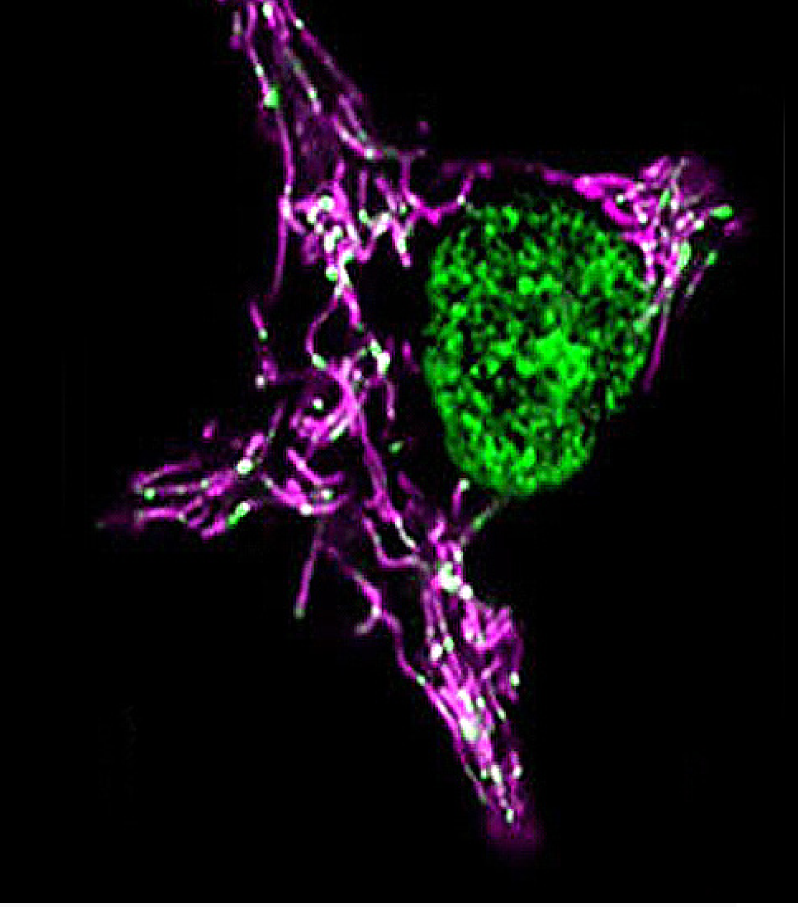
In short, mitochondria are not just powerhouses. They are central coordinators of life itself, integrating energy production with the biochemistry that makes complex organisms possible[16].

4. What does it mean to be a symbiont?

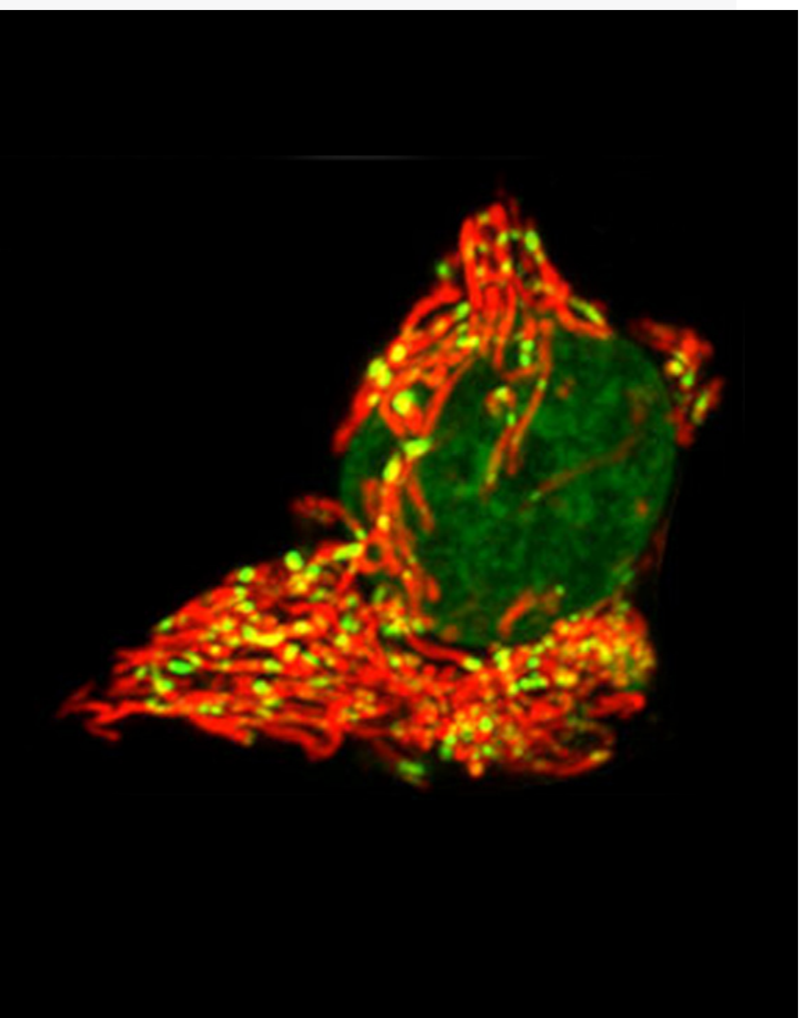
Symbiosis simply means "living together." In mutualism, both partners benefit. In commensalism, one benefits and the other is unaffected. In parasitism, one benefits at the other's expense[26].

Mitochondria adapted early in evolution as endosymbionts or microbes that lived inside another cell[27]. About 2 billion years ago, an archaeal host cell took in oxygen-using bacteria. Both sides gained something valuable: the host acquired a far more efficient way of producing ATP, and the bacteria gained protection and a steady food supply. This mutualistic partnership proved so successful that it transformed life on Earth, giving rise to the first eukaryotic cells.

Over time, however, the relationship deepened into something even more intimate. Mitochondria lost most of the genes they once carried, transferring them into the host's nucleus[10]. Today, only a tiny fraction of mitochondrial genes remain in their own genome[11]. Because of this integration,



"Nucleus and mtDNA (green); mitochondria (top image: magenta; bottom image: red); images by Dr. Dane M. Wolf."



mitochondria can no longer survive independently, and virtually all[28] eukaryotic cells cannot function without them.

In this sense, the modern eukaryotic cell is less a partnership and more a fusion of two ancient lineages. Mitochondria still carry traces of their bacterial past, but both their structures and functions are now so intertwined with the host genome that it is hard to think of them as separate entities.

5. Why do they have DNA?

One of the most striking features of mitochondria is that they carry their own DNA. This discovery provided decisive evidence that mitochondria evolved from bacteria[2]. Unlike the chromosomes in the nucleus, mitochondrial DNA (mtDNA) is small and circular[17]. Its size varies across species: plant mitochondria often harbor very large genomes, but animals, including humans, have much smaller ones.

Human mtDNA is only about 16,500 base pairs long; yet, it still encodes 37 genes: 13 proteins, 22 transfer RNAs, and two ribosomal RNAs[11]. The 13 proteins form essential components of the machinery that makes ATP, known as the OXPHOS system.

Compared with their bacterial ancestors, mitochondria have lost most of their original genes, which were transferred into the nucleus over evolutionary time[18]. The fact that many animal species from fruit flies to humans have conserved the same 37 genes for hundreds of millions of years suggests that these specific genes are retained in the organelle for important reasons.

Why not move them all into the nucleus? Several hypotheses exist. The proteins they encode are extremely hydrophobic (water-repelling), making them difficult and energetically costly to import once made outside. Keeping these genes inside mitochondria allows them to be expressed on site, giving the organelle more direct control over energy production under changing conditions. Because mtDNA mutates faster than nuclear DNA, retaining a small set of genes may help organisms fine-tune metabolism to adapt to temperature and environmental stresses[19]. Thus, mtDNA is both a relic of the past and a finely tuned tool for present-day survival.

6. How do mitochondria and the nucleus interact?

Mitochondria and the nucleus maintain a constant dialogue, because they share a range of responsibilities for building and maintaining one another. Notably, mitochondria carry their own DNA, but it encodes only a handful of proteins, which are necessary for the organelles' diverse functions. Well over 95% of mitochondrial proteins are encoded by nuclear genes, made in the cytosol, and then imported into mitochondria[10]. This means that close coordination between the two genomes is essential[20].

Communication flows in both directions. When mitochondria are stressed (for example, by damage or shortage of key nutrients), they send retrograde signals back to the nucleus[21]. These signals can include reactive oxygen species (ROS, chemically active by-products of respiration[22]) or small molecules, such as fumarate and acetyl-CoA. In response, the nucleus adjusts gene expression, producing protective proteins that help restore balance.

Conversely, the nucleus can send anterograde signals to mitochondria[23]. During challenges, such as nutrient shifts, cold exposure, or immune activation, the nucleus switches on genes that stimulate mitochondrial biogenesis and remodeling, tailoring the organelles to new conditions.

Physical proximity may also matter: studies show that mitochondria often cluster around the nucleus that could facilitate faster exchange of signals[24]. Above all, both genomes must remain compatible, because their protein products assemble together into the same respiratory complexes[25]. If this coordination breaks down, mitochondria cannot efficiently produce ATP, and cells, tissues, and whole organisms suffer.

7. How many roles do mitochondria play in physiology?

For much of the 20th century, mitochondria were known mainly as the "powerhouses of the cell", celebrated for their ability to generate ATP. While this description is true, it also narrowed the focus, leaving other crucial functions underappreciated[29]. That picture changed dramatically in the 1990s, when researchers discovered that mitochondria are also gatekeepers of cell death: the release of a protein called cytochrome c can trigger apoptosis[30,] a built-in program for removing damaged or dysfunctional cells.

Since then, our understanding of mitochondria has broadened enormously. Today, they are recognized as metabolic hubs at the center of countless processes. Mitochondria contribute, for example, to the production of heme (for hemoglobin and the electron transport chain), steroid hormones, iron-sulfur clusters (vital cofactors for enzymes and respiratory complexes), amino acids, nucleotides (for DNA and RNA), and various lipids. They are equally important in cellular communication, helping to regulate calcium levels, produce signaling molecules, such as ROS, and supply metabolites that influence gene expression[16].

Beyond metabolism and signaling, mitochondria also generate heat in brown fat (thermogenesis)[31], support immune responses by activating antiviral defenses[32], aid in detoxification and stress adaptation[33], and influence the behavior of stem cells, shaping tissue repair and renewal[33].

The 21st Century is witnessing a true renaissance in mitochondrial biology[29]. Far from being simple ATP factories, mitochondria are now increasingly recognized as highly versatile organelles that touch nearly every aspect of human physiology.

8. What do they mean for our health?

The health of the entire body depends, in many ways, on the health of its mitochondria. Every physiological process that defines life requires a steady flow of energy, and mitochondria provide the bulk of it in the form of ATP. When mitochondria work well, cells function normally, and the body's systems can maintain balance even in the face of many different kinds of stress.

Far from the static "bean-shaped" icons found in textbooks, mitochondria are highly dynamic[5]. They move around the cell, constantly merging together (fusion) or dividing (fission) to adapt to changing demands. Damaged mitochondria are selectively removed by a process called mitophagy[34], and new ones are created through biogenesis. In this way, the mitochondrial population within a cell is always renewing itself, sensing signals, and reshaping to meet energy needs[35].

The link between mitochondria and human health is perhaps most clearly demonstrated by VO2 max, the gold standard test of cardiorespiratory fitness and one of the strongest predictors of longevity[36]. VO_2 max measures how much oxygen the body can use at maximum effort, and nearly all of that oxygen is consumed by mitochondria. In effect, VO_2 max is a direct report on the quality and capacity of your mitochondria. Efforts to improve health through exercise or diet ultimately converge on these organelles. By converting the food we eat and the oxygen we breathe into usable energy, mitochondria sustain life, and their performance helps define how long and how well we live.

9. What do they mean for the future of treating diseases?

Mitochondria exist at the nexus of health and disease. They are the cell's central hubs of metabolism, and metabolism underlies nearly every major

health challenge of the modern world: cardiovascular disease, diabetes, cancer, neurodegeneration, and even aging itself[33]. Because of this, our ability to prevent and treat these conditions depends heavily on how well we understand and care for our mitochondria.

Modern medicine is often reactive, treating the symptoms of disease rather than its root causes. Yet many of today's leading killers share common origins in metabolic imbalance. Poor diet and lack of physical activity (e.g., directly impair mitochondrial function), and in doing so, they set the stage for chronic illness. On the other hand, improving diet and exercising regularly act as direct interventions in mitochondrial health, strengthening these organelles and, by extension, the entire body[37,38].

The future of medicine will increasingly focus on maintaining, restoring, and even optimizing mitochondrial function[39]. By identifying the factors that damage or support mitochondria, we can target the true foundations of disease rather than just its surface signs. This shift promises not only better treatments but also a deeper appreciation that many diseases are neither inevitable nor irreversible.

In this sense, mitochondria may hold the key to a new kind of healthcare—one that emphasizes resilience, prevention, and the potential for healthier, longer lives.

10. Why does modern medicine pay so little attention to mitochondria?

Only in recent decades has it become clear that mitochondria are far more than simple "powerhouses." As hubs of metabolism, they are woven into nearly every aspect of physiology. Yet modern medicine has been slow to adopt a "mito-centric" view of health.

One reason is the longstanding emphasis on genetics. For much of the last century, diseases, such as cancer, were seen almost entirely through the lens of mutations in nuclear DNA. While genetics is certainly of fundamental importance, we now know that many cancers are also strongly linked to metabolic dysfunction[40]. Conditions, such as obesity, can fuel tumor growth[41], and interventions that improve mitochondrial health (e.g., diet, exercise, or metabolic therapies) are proving to be powerful tools alongside genetic approaches.

Another reason is cultural. If mitochondria are part and parcel to our health, then lifestyle choices—what we eat, how much we move, how we manage stress—become direct interventions in our biology. That shifts responsibility away from pharmaceuticals and back onto our daily habits, a reality that does not fit neatly within a healthcare system heavily influenced by drug-based solutions.

The tide is turning as research continues to reveal the foundational role of mitochondria in aging and chronic disease, awareness is spreading, and this knowledge is empowering, too. By recognizing how our daily choices influence our mitochondria[42],[43], each of us can take an active role in shaping our long-term health and well-being.

In the same way that mitochondria are not static. Neither is human health. By better understanding these microscopic endosymbionts, we can better appreciate that our whole bodies are also highly dynamic and that every day offers new opportunities for change.

Click here for a complete list of article references.

Additional resources;

https://www.biointeractive.org/classroom-resources?keyword=mitochondria

https://ocw.mit.edu/courses/7-016-introductory-biology-fall-2018/resources/lecture-11-cells-the-simplest-functional-units/

https://wisconsin.pbslearningmedia.org/resource/tdc02.sci.life.cell.mitochondria/the-powerhouse-of-the-cell/

https://www.khanacademy.org/science/ap-biology/cell-structure-and-function/cell-structures-and-their-functions/v/mitochondria-video

About the authors:

Dr. Dane M. Wolf, a mitochondrial biologist specializing in advanced imaging technologies, completed his PhD at Boston University and University of California, Los Angeles. As an EMBO Long-Term Fellow at the University of Cambridge, he investigated mtDNA dynamics using cutting-edge imaging approaches. Dane is the founder of MitoGraphica, a scientific consultancy focused on mitochondrial image analysis and research. www.mitographica.com.

Gordon Freedman is the founder, president and board member of the National Laboratory for Education Transformation (NLET), www.NLET.org, which is the sponsoring nonprofit for MitoWorld. Freedman's interest and commitment to mitochondria issues grew out of his 10 year effort to decipher his own multiple health issues, which turned out to be mitochondrial in nature.

Freedman's personal mission is to help organize and "mainstream" mitochondria issues for the public, patients, the medical community and mitochondria labs, institutes and researchers. He believes the STEM-bio community could play a major role in updating how cells actually work.

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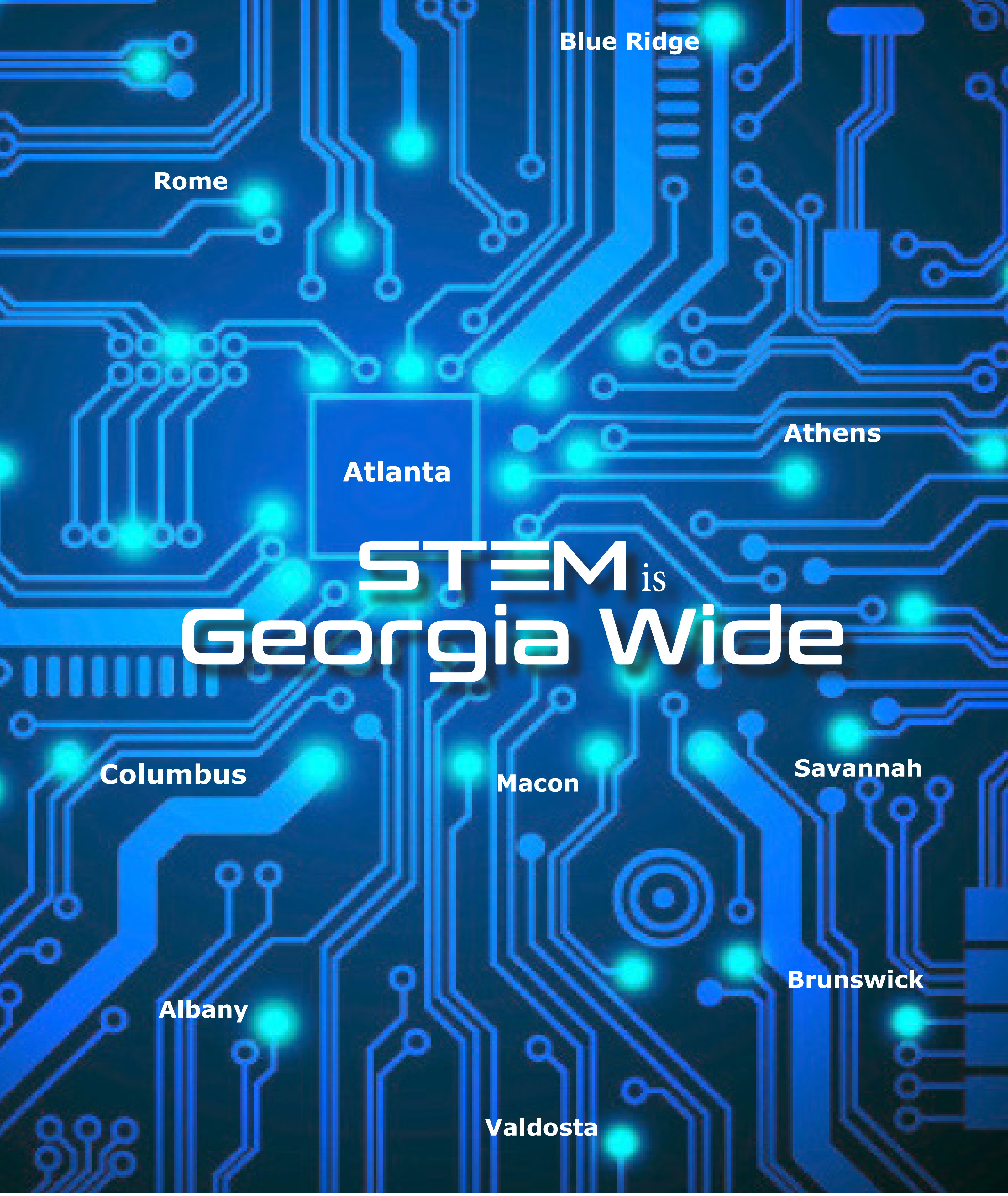

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