Experiments and Project-Based Enhancements for STEM Learning

Preprint

Robert Flores,[1] Analia Rao,[1] Kumaraguru Prabakar,[2] Meghan Pearson,[2] Yaswanth Nag Velaga,[2] Benjamin Kroposki,[2] and James Momoh[3]

1 University of California, Irvine
2 National Renewable Energy Laboratory
3 Howard University

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Experiments and Project-Based Enhancements for STEM Learning

Robert Flores, Analia Rao
University of California, Irvine
Irvine, California

Kumaraguru Prabakar, Meghan Pearson,
Yaswanth Nag Velaga, Benjamin Kroposki
National Renewable Energy Laboratory
Golden, Colorado
Email: kumaraguru.prabakar@nrel.gov

James Momoh
Howard University
Washington, DC

Abstract—**Motivating K–12 students to pursue careers in science, technology, engineering, and mathematics (STEM) is an effort that requires consistent engagement. Throughout the K–12 student timeline, STEM educators need to continuously pivot their teaching and update their educational materials to motivate the next generation of students. Once students begin their undergraduate education, university professors need to encourage them to consider pursuing graduate studies to ensure that a qualified future workforce can be developed for research and teaching. In this paper, we present our work on developing STEM materials for K–12 student engagement. Our K–12 materials target the grid integration of hydrogen assets that are suitable to engage students in the classroom. Our undergraduate materials target hands-on projects and collaboration with industry to connect classroom learning with real-world applications and needs in renewable energy. Our work leverages available open-source models and tools to create projects for undergraduate students and motivate their interest in pursuing research topics in graduate-level education.**

Index Terms—**K–12 STEM engagement, outreach materials, university outreach.**

I. Introduction

With every observation a student makes about the world around them, they are building on their science, technology, engineering, and math (STEM) identity. This is the part of self that identifies as being a scientist or engineer or mathematician. Traditionally, the responsibility lays at the hands of teachers, educators, and professors to help students explore their curiosity towards STEM. Science classes begin to explain observations made, such as why leaves change colors or why sour candies taste sour, but it is impossible for the classroom to answer every curiosity. This is possibly why, anecdotally and empirically [1], it is shown that people who have careers in STEM had influences outside the classroom to help them fall in love in STEM.

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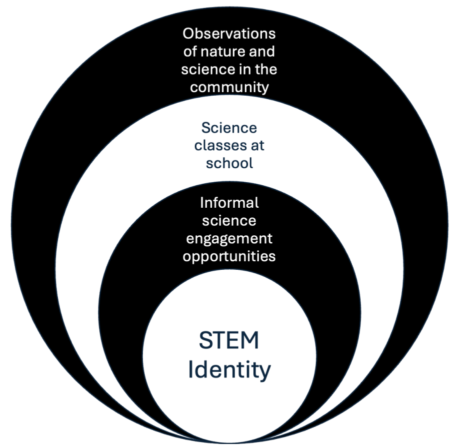

Fig. 1. Observations and experiences throughout a student's life build on each other to develop a student's STEM Identity

As Fig. 1 displays, it is the culmination of these many types of science interactions that lead to the final STEM Identity each person holds for themselves. Laboratories like the National Renewable Energy Laboratory (NREL) and others in the Department of Energy complex are stepping up to provide students and teachers a window into the research being done at their labs. Informal science programs and opportunities to interact with both the science and the scientists and engineers are giving students the chance to have their own anecdote of when they fell in love with STEM.

To support and create informal science programs and opportunities, we have worked and developed materials and programs that support students in kindergarten through undergraduate programs. A common denominator among these programs are experiment and hands-on projects that bring students and educators (teachers, graduate students) together. Our approach on using experiments and hands-on project has been supported in literature as valid tool for STEM teaching. Project based approach involving experiments and hands-on work for semester long course was discussed in [2]. Similar approach was also used in [3], where open source information and materials were used for experiment based projects that allows students to work as team towards a common goal. In [4], authors discussed the role of virtual and video experiments to foster STEM learning.

Finally, we made reporting as a formal requirement for the undergraduate students engaged in our work. Writing reports is a requirement for most engineers regardless of their career level. Engineering schools require students to write reports on the outcomes of their lab work, Recently, the literature has recommended that students include slides to present their written work [5], [6]. Slides are usually used for short-term explanations—that is, for the immediate presentation of the work—and text-based write-ups are used for long-term documentation of the work. For the STEM engagement work with undergraduate students, a formal report was required thus exposing students to the tools used in the report writing (creating images, taking screen shots of software developed, properly presenting plots and results, and citing appropriate past work).

In this paper, we first present our work on university led K-12 engagement, followed by the course outline developed by national lab for the audience to replicate in their student engagement. Finally, we present our work with undergraduate students and STEM.

II. University Led K-12 And Community College Student Engagement

The University of California, Irvine (UCI) Advanced Power and Energy Program (APEP) pursued two forms of educational outreach for K-12 students and community college students. First, APEP partnered with a local library to provide a science club for elementary and middle school children with the goal of exposing students to clean energy concepts using hands-on engineering experiments. Second, the APEP team hosted a series of on-campus events catering to high school and community college students with the goal of exposing students to what it is like to be an undergraduate engineering student, to perform research at the university setting, and why we work on clean hydrogen research. The following subsections outline these events, the APEP lessons learned, and the internal analysis of the success of the outreach methods.

A. Oak View Science Club - elementary and middle school student outreach

The science club convened at the Oak View library in Huntington Beach, CA. This branch serves a relatively low-income community and is closely located between an elementary school and a family resource center. According to California state analyses, this community is the only environmentally disadvantaged community south of Interstate 405 in Orange County. Similar events have been organized collaboratively between UCI and Oak View library.

The science club met four Wednesday afternoons during the summer break. During the meetings, the APEP team led between 20 and 40 elementary and middle school children through the following activities:

1) Build a device to protect an egg when dropped from 10 feet or higher.
2) Build paper airplanes and try to design planes that fly farther and longer.
3) Construct a wind catcher and identify the strongest wind location—near the library building or in an open field.
4) Construct simple DC circuits using small solar panels, LED lights, and electric motors. Examine panel orientation to identify the strongest LED lighting effect and motor speed.
5) Perform water electrolysis experiment using saltwater, graphite, and a battery. Then replace the battery with a solar panel and repeat the experiment outside.
6) Construct a homemade electric motor using a battery, paper clips, magnet, and wire coil.
7) Construct marshmallow-spaghetti bridges and test how much weight the bridges can hold.

B. University Campus Visit for High School and Community College Students

APEP hosted three separate visits. The first visit included approximately 50 students from the National Science Foundation-funded Scholarships in Science, Technology, Engineering, and Mathematics (S-STEM) summer bridge/transition program who are transferring from local community colleges to UCI. The goal of S-STEM is to increase the number of low-income community college students who graduate with an engineering baccalaureate degree and enter STEM graduate school and/or the workforce. The purpose of the S-STEM summer bridge program is to introduce transfer students to different opportunities available to them as STEM students at universities.

APEP supported these goals by 1) introducing transfer students to the concept of undergraduate research at UCI and 2) allowing them to ask current APEP graduate student researchers questions about their path to academic research. To accomplish this, APEP gave a 45-minute presentation on the role of hydrogen in a clean energy future, provided a tour of APEP laboratory facilities and experiments, and hosted a Q&A session between APEP graduate and undergraduate researchers.

The second visit included approximately 30 students from the Achievement Institute for STEM Scholars, a nonprofit organization aimed at supporting high-achieving, low-income students in Orange County to gain acceptance to major colleges and universities in STEM fields. APEP supported these goals by 1) facilitating interactions between institute scholars and APEP undergraduate researchers to discuss what it is like to be an undergraduate engineering student, 2) introducing the scholars to research as a form of university education and advancement, and 3) introducing the scholars to APEP research topics. The visit featured many of the same aspects as the S-STEM visit, in addition to a hands-on experiment session and lunch with APEP researchers. The experiments included constructing an electric motor using a battery, magnet, paper clips, and wire coil; and a separate water electrolysis experiment where students split water into gaseous hydrogen and oxygen using saltwater, a battery, and two pieces of graphite.

The third visit included approximately 50 students from the Samueli Academy, a charter school serving grades 7–12. The school has a dedicated engineering curriculum and promotes STEM career pathways for students. The students toured the APEP facilities and the UCI campus and listened to a brief lecture on energy sustainability.

C. Lessons Learned from the University Led Outreach Events

The lessons learned and evaluations of the different outreach methods are based on anecdotal responses from program participants and speculation from APEP engineers. We will modify our strategies based on these evaluations, and we are hopeful that they will improve the outreach outcomes:

1) Interactive experiments: The most effective outreach methods consist of direct interactions between APEP student researchers and visitors/science club participants. Less structured interactions occurring around a hands-on experiment, lunch, or a panel discussion on life as an engineering student at UCI led to more consistent and engaged conversations that could be steered toward STEM topics due to the laboratory and university setting.

2) Facilities tour to simulate life experiences as a STEM student: The most memorable experiences grow out of simulating life as a college student and conducting hands-on experiments. Responses from participants of the Section 1.A events indicated that, when offered, the more enjoyable parts of the visit were, in order, eating lunch at a UCI cafeteria, touring the UCI campus and APEP laboratories, and conducting hands-on experiments. The least enjoyable experiences were listening to lectures and discussing why we research clean energy and sustainability.

3) Budget allocation for events: The project budgets need to include support for effective outreach. In many instances, the project proposals neglected serious considerations of outreach, resulting in a reliance on laboratory tours and classroom-style lectures because these methods are low cost, but the most successful outreach events included higher-cost activities. In many instances, equipment for hands-on experiments can be bought once and reused multiple times, making them cost-effective; however, providing meals incurred costs on par or exceeding experimental material costs and exceeding budget expectations, resulting in a request for special approval. In addition, organizers should also consider supporting potential transportation cost while building the budget.

4) Possibilities of academic credit to student volunteers: The participation of APEP student researchers and engineering students is critical to the success of any outreach event, but providing their support does not provide a direct benefit to meeting their requirements to graduate. Thus, it is necessary to develop a laboratory culture that sufficiently supports outreach events and establishes repeated outreach success. This could be difficult to implement because an academic research setting can require critical feedback on students' engineering work. To achieve this, it is important to focus on a culture that is academically rigorous, encourages constructive criticism, and adjusts to the research pace of individual students while providing emotional support.

5) Colloboration with non-traditional academic institutions: It is essential to establish and maintain a positive relationship with local libraries and schools to ensure success. Librarians in particular are experts in developing and executing community outreach programs, including scheduling, advertising, and administration. In our experience, librarians will support STEM outreach and will use their time and knowledge to help fill planning gaps.

6) Planning for photo releases: It is important to use photo releases that allow for showing the faces of outreach participants. Because these outreach events are funded by separate projects, reporting on the outcomes is easier through the use of photographs and/or videos. Additionally, subsequently advertising new outreach events is enhanced by using media from prior outreach engagements.

III. Research lab led STEM outreach materials

This section presents the materials developed by a research lab (NREL) to connect the application of STEM classroom concepts to current research.

A. Content to Engage and Inspire the Workforce of Tomorrow

For decades, STEM has been taught through a historical story line. Textbooks teach students STEM in order of discovery to help the students gain an appreciation of where the sciences started and to better understand where they are now. But because of the length of time that schools rely on the same textbooks—often decades—it can be hard to work new technologies into these lessons. Institutions like the National Renewable Energy Laboratory (NREL) and UCI have an obligation to the next generation to help bridge these gaps in information. By developing downloadable packages of material that teachers can easily leverage in the classroom, students can gain an understanding of how the sciences from from the textbooks are being applied in labs around the world today. Students can begin to build their STEM identities—the foundational development of how a person sees themselves interacting, understanding, and being part of the STEM community—with a better understanding of the research being done and the paths that lead to careers in those fields.

B. Collaboration between workforce Development Team and Researchers

NREL's workforce development team partnered with researchers from power systems engineering team to build a short course that can be downloaded and taught by community members, teachers, and professors who are interested in getting students and community members excited about the future of hydrogen as both fuel and energy storage. Leveraging scientists and engineers from across multiple fields, we are working to develop a course that approaches hydrogen

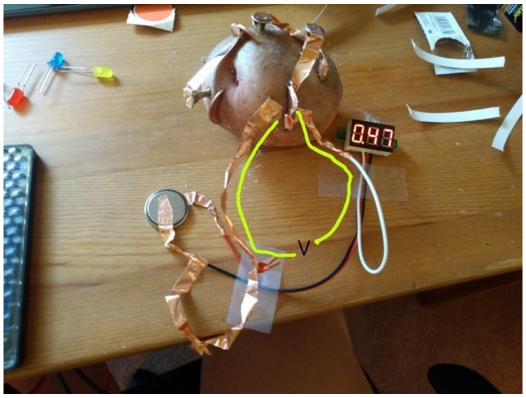

Fig. 2. Building a potato battery and measuring voltage output.

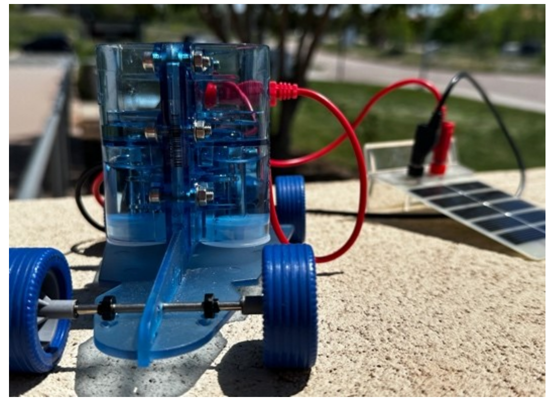

Fig. 3. Hydrogen car experiment using solar power to split water.

through three pillars: chemistry, engineering, and economics. This course is being designed for use by teachers looking to add new technology discussions to their classrooms and by community members looking to generate excitement about new clean energy technologies. It is meant to present current challenges as well as successes in the applications of hydrogen. All decisions about the necessary materials were intended to make the course and its experiments easy to implement in most locations and with most budgets.

C. Development of the Course

A small team of scientists, engineers, and K–12 content specialists have been developing a comprehensive overview of hydrogen and the work being done as it relates to chemistry, engineering, and economics. We identified these three topics because of the work performed in the lab, their relationship to the next generation science standards, and their applicability to a clean energy future. The short course is designed to align with at least two standards in each content area, which will be clearly identified in the material to ensure ease of use for teachers. All the materials are targeted for an approximate seventh-grade science understanding, but the presentations will be easy to update to allow presenters to tailor them to their specific audience. All the topics in the short course should take approximately 1.5–2 hours to complete, but the full series is not meant to be completed within 1 day. Each topic will include macroscale model activities, lectures categorized by "understanding check" activities, and an experiment to display the concepts learned that day. As designed, the experiments and activities will all rely on food-grade or easily purchasable items that can be found at stores, or at internet marketplace.

TABLE I
STANDARDS

HS-PS1-2	Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.
HS-PS1-4	Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends on the changes in total bond energy.

1) Chemistry Pillar: The chemistry pillar will explore hydrogen as an element. Students will learn about the smallest element on the periodic table and its chemical properties. This will lead to learning about chemical reactions, specifically reduction and oxidation reactions, and the basics of electrochemistry. This will help form the foundations of the students' undertanding of the chemistry of a fuel cell, hydrogen's use as energy storage, and the energy difference between breaking apart water and the output of hydrogen. Experiments for this topics will include:

i. Potato battery: Explores voltage potential differences using different metals and different produce. Students will begin to understand that batteries work by exploiting electron transfer during some reactions. This sets the tone for hydrogen working like a battery. The setup used for this experiment is shown in Fig. 2.
ii. Splitting water with a 9-V battery: Explores what happens when electricity is put into a system rather than being taken out of a system. Although hydrogen is not collected, the stoichiometry is visible by studying the two electrodes and the bubbles produced. This sets up the conversation about the amount of energy needed to split water compared to the amount of energy stored in hydrogen.
iii. Combustion vs. fuel cell (demo): Explores the differences between a fuel cell and combustion. Students will gain an understanding of why a hydrogen car is considered an electric vehicle.

TABLE II
STANDARDS

HS-PS3-3	Design, build, and refine a device that works within given constraints to convert one form of energy into another.
HS-ESS3-2	Evaluate competing design solutions for developing, managing, and using energy and mineral resources based on cost-benefit ratios.
HS-ETS1-1	Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

2) Engineering Pillar: The engineering pillar will explore challenges in designing systems for hydrogen as both a fuel and energy storage. Students can apply what they learned during the chemistry pillar to reason through the engineering challenges. They will learn about hydrogen being used as both a grid-forming and a grid-following energy system and its application in the clean energy future. Experiments for this topic will include:

i. Balloon blow-up: Explores how temperature and pressure affect gas expansion and contraction. Students will design systems to maintain consistency in their balloon size.
ii. Vehicle comparison game: Explores the pros and cons of different types of vehicles using techno-economic analysis. Students will begin to see the differences between different fuel types. This will include experimentation with the different types of vehicles. One of the vehicles used in this experiment is shown in Fig. 3.
iii. Building a grid: Explores the integration of multiple energy sources to understand how they will all need to work together to power a grid. Students will begin to understand the challenges of integration as well as the uses of different sources on the grid of the future.

TABLE III
STANDARDS

HS-SS3-1	Productive resources (natural, human, capital) are scarce; therefore, choices are made about how individuals, businesses, governments, and nonprofits allocate these resources.

3) Presentation of the short course: Based on previous short courses that we have developed and presented, we will present portions of this short course in conjunction with the celebration of International Women in Engineering Day. From the lessons learned, partnering these lectures/experiment series with an event that already has an audience draws increased participation. We will present the materials as written, and we will do a pre- and post-knowledge survey to learn more about what students take away from the program.

IV. Project Materials Targeting University Level Students

In this section, we present our project based learning materials developed to keep the undergraduate students engaged in STEM and choose a career in STEM (rather than moving to a different non-STEM domain) or choose to continue towards graduate degree and perform graduate level research work. The Howard University Center for Energy Systems and Control (CESaC) has developed a pedagogy of education and research emphasizing the integration of cutting-edge technology tools across all academic levels through teaching and research. The program leverages state-of-the-art infrastructure facilitated by the digital real time simulators (DRTS). The DRTS has been instrumental in facilitating research that led to the recent graduation of several graduate students with research experience in the areas of volt-VAR control, frequency control, and cybersecurity issues in microgrids. These graduates are now Ph.D. students who are teaching at different universities and contributing to research in the energy and power systems areas. Following is an overview of the projects and initiatives aimed at preparing students at all academic levels for careers in next generation of engineering analysis.

1) Sophomore Level (Undergraduate): Students are exposed to concepts of three-phase AC power and explore various connections of AC, including wye-wye, delta-wye, wye-delta, and delta-delta configurations. They applied the concepts learned in fundamentals of circuit theory class to calculate voltage conditions and power flows within the network.

2) Junior Level (Undergraduate): Students receive a comprehensive background in renewable energy, machine characteristics, and magnetism. Then, they transition to introduction to power systems, where they engage in power flow studies and learn to compute complex power. They gain insights into the network's performance under diverse conditions, enhancing their understanding of power system dynamics.

3) Senior Level (Undergraduate): Seniors delve deeper into power system analysis, focusing on topics such as economic dispatch. They explore advanced concepts to develop a holistic understanding of power systems and their components.

4) New Graduate Students: Graduate students with a background in power further extend their knowledge through rigorous studies in power flow analysis, stability studies, fault analysis, power electronics, and renewable energy.

The courses are structured such that the students can do hands-on work, which includes DRTS software (electromagnetic transients domain) and hardware, in solving different project assignments in each class group. Through collaboration with U.S. department of energy national labs, we have developed a national lab-university site visit to engage in different research work at university level through training provided by national lab researchers on how to use DRTS. National lab researchers have generously dedicated their time and expertise, both online and on-site, to offer training sessions and provide access to test beds for simulation projects.

The DRTS is currently being used to equip undergraduate students and current graduate students with skills and capabilities to solve microgrid and distribution system challenges. This endeavor has extended to include high-school students through the pre-college engineering systems outreach program the summer at CESaC. These students gain experience in electrical engineering, power systems, and the use of advanced simulation tools. With hands-on experience in DRTS, students successfully completed the following four projects, and the outcomes are discussed next.

A. Fault Studies for a Digital Twin of test system:

In this experiment, DRTS software and hardware are used to study faults on the two-feeder Banshee distribution network [7]. The graphical user interface is responsible for applying the fault controls, recording the data, and accessing the plots. The students analyzed the impact of different types of faults at the grid bus of the network, including three-phase, double-line-to-ground, and single-line-to-ground faults. This experiment improved the students' understanding of faults in relation to microgrid power systems.

B. Digital Twin Based Balanced and Unbalanced Load Study:

This experiment entails analysis of balanced and unbalanced loads within the Banshee distribution network. Through simulations and studies using the DRTS software and hardware, the students explored the implications of load balancing on operational efficiency and safety, particularly focusing on specific loads within the network. The results showed the students that during balanced conditions, the negative- and positive-sequence currents are 0, and the value for the positive-sequence current was equal to the root-mean-square value of the branch current. The experiment delves further into the unbalanced load conditions as well.

C. Banshee Distribution Network Modification and Microgrid Controller for Outage Study:

This experiment entails the adaptation of the Banshee distribution network to match the processing capacity of the DRTS at CESaC. Through cross-rack simulation, we successfully implemented Banshee feeders 1 and 2 . We conducted a load flow study post-implementation to evaluate the network performance. We will implement a more comprehensive contingency analysis on this network and then analyze its impact on this test bed. We will address loss-of-line, loss-of-generator, loss-of-line, and loss-of-transformer contingencies and faults at different locations on the network. Based on the results, we will analyze the impact of each contingency scenario, and we will develop appropriate controls. To properly address the load frequency control on the Banshee distribution network, we will incorporate a wind turbine into the modified Banshee network.

D. Inverter-Based Distributed Energy Resource Integration:

Students under research experiences for undergraduates program investigated the integration of inverter-based resources and distributed energy resources on microgrids using the Banshee network to address volt-VAR and protection issues. The work also includes studying the impact of placing inverter-based resources at different locations in the network to determine the optimal sizing and locations.

E. Lessons Learned

We successfully bridged the gap between research and education. Now, industry-level design and specification requirements, once difficult for students to grasp, are seamlessly integrated into their problem-solving process. This hands-on experience has empowered students to apply theoretical knowledge from the classroom to practical systems, fostering a deeper understanding. Moreover, it has cultivated essential skills, such as teamwork and time management. Embracing a team-based approach, students collaborate in diverse groups at various times while being supported by graduate students and faculty members at CESaC. Notably, this initiative has nurtured leadership abilities. Each team has a lead member who dedicates extra lab hours to project development. Our students under research experiences for undergraduates program and graduate students now benefit from invaluable practical exposure.

Further, we gathered feedback through a student survey, revealing that many deem practical real-life applications essential for their education at Howard University. Some comments are as follows:

1) "This outreach has not only bridged the gap between research and education but has also provided insights into industry practices. We observed industry professionals utilizing advanced real-time digital simulators to teach concepts like measuring current and power systems".
2) Another student stated, "The NREL visit offered hands-on experiences, aligning classroom knowledge with practical applications, and provided insights into complex power systems like the 20-bus power systems".

This outreach has truly ignited students' enthusiasm for project-based learning, resulting in initiatives like building a digital twin with DRTS and a heartbeat monitor with filter knowledge. The visit increased the understanding of the students about vital industry topics like microgrids with the use of DRTS software and hardware, thereby expanding their knowledge base and enthusiasm in the power and energy systems areas. It also inspired students to pursue advanced education, including master's and doctoral programs. The graduate students have also gained the invaluable experience needed to confidently conduct their research.

V. Conclusion

In this paper, we presented our work on STEM engagement in the K-16 audience. The materials developed hope to engage the next generation of scientists and engineers, from kindergarten through their senior year in college in the challenges of renewable energy integration. The approach we took in developing outreach materials is to focus more on experiments and the student-researcher (or student-industry mentor) engagement, with the ultimate goal of continuous, intentional touch points throughout the students scholastic career to encourage them to pursue careers in STEM.

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