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Collaboration Across Disciplines for Sustainability: Green Chemistry as an Emerging Multistakeholder Community

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Sustainable solutions to our nation's material and energy needs must consider environmental, health, and social impacts while developing new technologies. Building a framework to support interdisciplinary interactions and incorporate sustainability goals into the research and development process will benefit green chemistry and other sciences. This paper explores the contributions that diverse disciplines can provide to the design of greener technologies. These interactions have the potential to create technologies that simultaneously minimize environmental and health impacts by drawing on the combined expertise of students and faculty in chemical sciences, engineering, environmental health, social sciences, public policy, and business.

INTRODUCTION

Achieving a safe operating space for humanity within planetary biophysical boundaries (e.g., climate change, change in land use, and chemical pollution) requires major contributions from chemistry.[1] The chemical industry provides critical technologies that support complex societies through energy, transportation, and food infrastructures as well as countless consumer products. Globally, the chemical industry uses significant material resources and fossil fuel energy and produces greenhouse gas emissions, pollution, and waste in manufacturing.[2−4] These byproducts can affect the health of humans, wildlife, and ecosystems, as seen through endocrine disruption of organismal reproduction and development.[5] In response, green chemists proactively seek to reduce chemical hazards and increase societal sustainability through redesign of molecules and reactions.[6]

There have been numerous calls for chemistry, along with many other sciences, to become more interdisciplinary in research, teaching, and commercialization. Chemists have worked on technology-related sustainability problems for over 25 years. The National Academy of Sciences has repeatedly included sustainability in general, and green chemistry in particular, as part of the long-term research and development agenda in the chemical sciences.[7]

The sustainability goals that green chemistry seeks to address involve complex social, ecological, market, organizational, and scientific issues that span global production chains, multiple temporal and spatial scales, and societies.[10,11] Green chemistry began in the early 1990s as an initiative of chemists and knowledgeable policy-makers.[8] The field has made promising progress as seen in the annual Presidential Green Chemistry Awards, growing numbers of technologies and patents, and changes in business organizations to promote greener innovation.[9] To successfully engage academic partners across a spectrum of disciplines, the full complexity of technology research, development, implementation, and evaluation must be considered.

Successfully engaging diverse disciplines can help identify important sustainability issues that researchers can overlook in an isolated disciplinary context. A frequently cited example is the lack of chemist exposure to toxicology in their education, leading to failure to consider the toxicity implications of molecular design choices.[12] Other gaps in knowledge include the lack of engagement of chemists in societal debates over what sustainability means and failures of policy-makers and business managers to appreciate how chemists develop new technologies. Such neglect grows from the historical paucity of collaborative interactions between chemists and other disciplines due to many educational, industry, and professional barriers.

Academic green chemistry education and research, like other sciences, could benefit from greater collaboration between the many disciplines involved. At present, the rich potentials of green chemistry still remain largely unrealized. Thus, we propose an integrated approach to generating and using expert input, through creating new incentives and venues for interaction to draw in and combine different disciplines. We also discuss how collaborative university-based teams can catalyze the next generation of green chemistry tools and technologies. These suggestions can benefit other scientific endeavors too.

AN INTERDISCIPLINARY APPROACH

By interdisciplinary, we mean a spectrum of ways in which natural scientific, policy, social scientific, engineering, business, and public health disciplines interact and integrate with each other in researching, implementing, and evaluating green

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Table 1. Comparison of Disciplinary Research Priorities[a]

Discipline	Basic Research	Development	Implementation	Evaluation
Chemistry	High	Moderate	Low	Moderate
Chemical Engineering	Moderate	High	High	Moderate
Toxicology	High	Low	Low	High
Environmental Science	High	Low	Moderate	High
Public Health	Moderate	Low	Moderate	High
Business	Low	Moderate	High	Moderate
Public Policy	Low	Moderate	High	High
Sociology	Moderate	Low	High	Moderate
Science and Technology Studies	Moderate	Low	High	High

[a]**Basic Research**: Research aimed at the discovery of new quantifiable phenomena that could lead to technology development. **Development**: Research aimed at creating new technologies with specific outputs. **Implementation**: Research aimed at elucidating the drivers and barriers for the adoption of new technology in industrial and societal settings. **Evaluation**: Research aimed at determining the effects of new technology on society, health, and the environment.

chemistry.[13,14] Researchers can share their expertise in many ways. For example, some researchers may combine methods from both chemistry and environmental science in their own projects, while others may participate in diverse research teams without being themselves interdisciplinary, and social scientists may draw on scientific literature in designing their studies.[14]

Two barriers to successful interdisciplinary collaboration are (1) the differences in cognitive models and problem-solving processes that various disciplines rely on because of their professional training and practice[15] and (2) the divergent research and problem-solving priorities that these disciplines have when studying technology related fields. These barriers often inhibit effective communication and transfer of information from one discipline to another. This results in information being lost along the path from basic science to technology development and eventual societal adoption of new products and processes.[16] We provide examples of these divergent cognitive models and priorities below.

Various disciplines often focus their research effort on only one or two aspects of the creation and adoption of new technologies. These technologies emerge through interrelated, cyclical, nonlinear phases (basic research, development, implementation, and evaluation) with the participation of numerous technical, social, and political actors.[17,18] Scientists can conduct basic research that helps produce the science embodied in a new technology. Other scientists, engineers, toxicologists, and business experts can scale up and commercialize the technology in an industrial and societal context. Public health, policy, and social scientists can help create and evaluate new data for the technology's environmental and health impacts, before cycling this data back into basic research and implementation in a trial-and-error learning process.[19] The associations between disciplines and the phases of technology development are qualitatively summarized in Table 1. A discipline prioritizes a research area from high to low according to the level of attention of researchers, the density of funding opportunities, and the creation of training and research programs.

The variation in cognitive models and priorities between the disciplines is both a strong barrier to, and an exciting opportunity to benefit from, interdisciplinary collaborations. Effective collaboration needs an alignment of professional goals with the diverse skills and cognitive models that researchers can bring so that synergies can emerge. Yet most researchers have believed that they are unlikely to benefit professionally from drawing on skills and knowledge from beyond their disciplines. They do not see a lack of cross-disciplinary collaboration as a problem.[15] A key challenge is to formulate goals that are meaningful and motivating across disciplines while recognizing different research priorities and cognitive models. The principles of green chemistry, for instance, may help support these goals but do not define how specific disciplines could approach the development of sustainable technologies.

The goals of green chemistry, achieving safer and more efficient chemicals and processes, have mobilized diverse interest in improving the sustainability of the chemical enterprise. No single discipline has the full knowledge required to achieve these sustainability goals through green chemistry, which makes it an ideal testing ground for the integration of interdisciplinary knowledge. Despite their best intentions, green chemists can still generate adverse consequences by failing to recognize the environmental and social impacts of their design choices, because they are not asking appropriate questions or having their work evaluated by other experts who can provide different perspectives.[8] There may also be gaps between data derived from quantitative (e.g., numerical estimates of toxicity and molecular properties) and qualitative (e.g., observations of how products are used in households, surveys of chemical risk perceptions) sources.[15]

Sustainability demands the *integration* of multiple forms of knowledge, including natural scientific, health, social scientific, commercial, and policy, across the entire life cycle of chemicals.[20,21] By integration, we mean that chemists do not restrict their sources of information to chemistry or work primarily with other chemists but collaborate within a field of experts in toxicology, business, law, policy, and social scientists in considering solutions. These experts may also work with societal actors, such as governments, NGOs, and companies, who are knowledgeable about barriers and opportunities that can help frame problems and solution sets. The need for integrated problem-solving approaches to green chemistry can be seen in an example of developing clean energy technologies below.

MAKING BARRIERS TO COLLABORATION MORE PERMEABLE

Historically, in doing academic research, scientists, toxicologists, and engineers have concentrated on individual chemicals, reaction pathways, or technologies in isolation, rather than seeing these as part of larger ecological and socio-economic systems.[22] Some green chemists have begun to analyze these larger systems, acknowledging that some chemicals may be green in certain ways but be unsustainable in other ways.[23,24] Likewise, sociologists, public health experts, and innovation experts have often focused on chemicals in isolation and have seldom studied chemicals as part of industrial systems and societal uses.

Significant knowledge and institutional barriers inhibit experts from multiple disciplines from effectively communicating and interacting with each other and with societal actors more widely.[15] Chemists, toxicologists, economists, engineers, sociologists, and public health specialists have been trained according to particular educational models. They are immersed in disciplinary research cultures and professional norms that influence who they work with, what types of problems they choose, how they conduct research, how they report their results, and how they turn their work into technologies. Thus, many disciplinary researchers may be unprepared to address problems outside their expertise, though they are capable of doing so. Similarly, many natural scientists, policy analysts, social scientists, and business experts are reluctant to engage with technical debates because of their lack of experience with doing, not just observing, research in other fields.

Researchers from multiple disciplines may be reluctant to take risks of expending time and resources on a venture that may not directly benefit their own work. They may have divergent views on what "sustainability" means, which may seem insurmountable. For example, social scientists may seek more contextual, historically grounded definitions of sustainability, whereas chemists may be more inclined to apparently value-neutral quantitative meanings.[15] Social scientists may presume that they know what chemistry means — as the cause of pollution for example — without endeavoring to understand how chemistry is practiced. Conversely, chemists may sometimes regard environmental and social issues as less "scientific" topics because these are not readily quantified or reduced to well-bounded domains.

Many disciplinary experts, especially chemists and some social scientists, also tend not to engage in political or regulatory discussions because they wish to comply with their professional norms and have few incentives to diverge.[8] They rarely participate in larger public discourse targeted at enhancing societal capacity to make collective decisions on chemical production. Instead, they prefer to contribute to the political process only through narrowly defined technical advisory committees that remain insulated from larger social, economic and political discourse. Chemists do join public education efforts such as high school programs and are frequent participants in scientific advisory bodies like the National Academy of Sciences and the California Green Chemistry Initiative Science Advisory Panel. A large number of scientists, including chemists, now practice policy-relevant research in government laboratories such as EPA and the Department of Energy. Their work remains largely quantitative in character, thus potentially marginalizing important qualitative and ethical considerations. Similarly, policy analysts, business experts, and economists often participate in policy-making processes and public discourse because their disciplinary training and incentives encourage them to. Yet they may not focus on green chemistry issues specifically due to their lack of awareness. Their expert input may still embody disciplinary perspectives.

A limited number of professional and institutional venues exist where scientists, policy analysts, public health experts, business managers, and others can communicate with each other. These venues could include journals, conferences, professional associations, company boards, design studios, and teaching programs that are dedicated to multiple disciplinary perspectives or to holistic analysis. Segregation into disciplinary groups tends to prevail as a traditional practice. Thus, little mutual learning occurs between disciplines and between disciplines and societies. Most importantly, chemists and engineers who develop or modify technologies do not receive feedback from the assessment of social and environmental impacts until well after the technologies are deployed and impacts have begun to appear. This is partly because they are disconnected from experts who may be monitoring the impacts and who could inform their design.[8] European policy analysts have identified this lag in knowledge as a major cause of many chemical problems.[25,26]

To overcome barriers to communication, researchers, universities, companies, and policy-makers can build an iterative, cyclical process for collaboration in academic research. Figure 1 shows how disciplines can be integrated into this cycle.

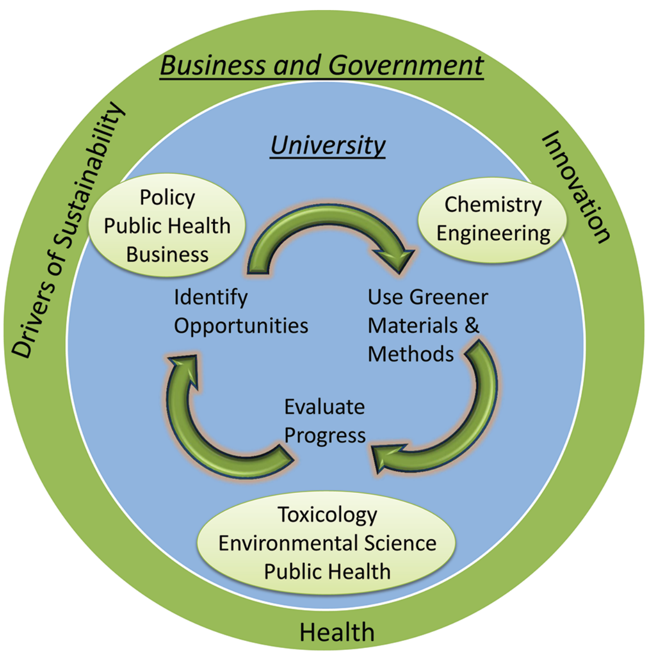

Figure 1. Integration of disciplines into a cyclical process.

In the blue circle, chemists and engineers design molecules whose potential impacts are evaluated in advance by toxicologists and public health experts. The green circle highlights how public policies, business strategies, and political contexts can affect the adoption of these molecules. Projects may originate at any point in the cycle, and each project will pass through each of the phases in an ongoing process of identifying opportunities for greening chemistry, developing greener materials and methods, and evaluating progress. A project can originate in any discipline and still be influenced extensively by other disciplines as it takes form and is implemented over time and space. No single discipline has preeminent influence over the development and evaluation of a technology. How this cyclical, trial-and-error research and development process can work is illustrated below through examples drawn from clean energy technology development.

■ INTEGRATION IN GREEN ENERGY TECHNOLOGIES

Clean energy and global environmental pollution are two of the most significant sustainability challenges. Unfortunately, traditional research and development approaches have often treated them as only passingly related issues. By applying the methodologies of green chemistry to energy technology research, it becomes clear that much can be gained from an integrated, systems approach to sustainable technology development. A National Research Council study estimated that in 2005 alone, the US energy production system caused over $120 billion of externalized nonclimate change harms (as measured through health, environment, security, and infrastructure effects) across the life cycles of fossil fuels, nuclear energy, and renewable energy sources.[27]

Many environmental and social impacts of energy technologies have been recognized or assessed only after their wide deployment, when these impacts are most visible and easiest to measure. Yet it is most feasible to minimize or prevent the impacts through creative design during earlier phases of research and development. Safety and efficiency gains made during these phases will result in significantly fewer costs and impacts during the deployment, use, and end-of-life stages. Developing clean energy technologies such as biofuels and photovoltaic panels that are truly sustainable will require a systems approach that considers multiple environmental and social impacts of new energy generation.

A. Identify Opportunities. Policy, business, environmental science, social science, and public health researchers can investigate what new possibilities exist for using green chemistry in developing biofuel and photovoltaic (PV) technologies. For example, they can analyze the existing environmental and social impacts of biofuel production across life cycles, evaluate policy trends, and scrutinize the market to see what energy technologies are prevailing in implementation. In so doing, they may identify needs that are not yet being met.

Promoting biofuels offsets the use phase impacts of gasoline,[28] but their extraction and processing phases may still generate sizable environmental and social effects, depending on the feedstock type and agricultural system. Using industrial agriculture methods to produce corn, sugar cane, and other biomass needed to supply biofuels at large scale can demand significant amounts of land, water, fertilizers, herbicides, energy, and other agricultural inputs, contributing to water depletion, wildlife habitat destruction, and harm to rural community health.[28−31] Expanding crops for biofuel production in a region can cause indirect land use impacts through driving the conversion of forests and grasslands to cropland elsewhere to substitute for lost food production capacity in the original region, thus producing significant net greenhouse gas emissions.[32] Conversely, adopting more sustainable agricultural methods such as integrated pest management, crop rotations, and more diversified landscapes providing ecological services could improve the environmental footprint of biofuel production in principle.[33]

Researchers can contribute to understanding the impact of green chemistry by asking questions about how businesses, policy-making agencies, and city governments can improve conditions for incorporating it into biofuel and photovoltaic infrastructures though procurement, regulation, and urban planning. Many social actors also have a stake in the continuous improvement of the chemical industry. While they may not directly participate in developing chemicals and processes, they can affect the adoption of green chemistry. Retailers, investors, and consumers preferences for safer chemicals flow through supply chains into the design actions of chemical producers. By partnering with these off-campus stakeholders, researchers at universities have the ability to capture and analyze these preferences and to help influence technology design accordingly.

B. Use Greener Materials and Methods. Having understood opportunities for improvement, chemists and engineers can develop new materials and prototypes for biofuel and PV technologies. By targeting the opportunities identified and characterized by colleagues, these new materials and models have a greater potential for social acceptance and economic success. For instance, life cycle assessments suggest that using lignocellulosic and cellulosic feedstock for biofuels could help reduce these impacts, depending on where they are sourced from and what technologies are used to grow them.[34,35] Green chemistry research is underway at many institutions, as well as in companies, to address these challenges through technological improvement applied throughout the biofuel life cycle. Similarly, green chemistry research into PV technologies now focuses on materials that are safe and abundant with the recognition that these materials will be more amenable for deployment on global scales.[36] An integrated green chemistry approach helps chemists identify the materials that minimize the environmental impacts throughout their life cycle.

Chemists trained in this manner can explain and characterize the potential technical advantages and limitations to colleagues in policy, public health, and business disciplines long before new technologies enter the marketplace. These discussions during the early phases of technology development give researchers greater insight into important health, market, and environmental considerations. These interactions also give researchers focused on technology adoption insight into emerging technologies as well as confidence to explore their technical aspects. This perspective can assist policy-makers and business managers by showing how green chemistry design tools will enhance proactive decision-making. Using interdisciplinary input, the green chemistry framework helps guide technology development toward new materials that are inherently safer and more efficient.

C. Evaluate Progress. To ensure that advances are indeed greener, new materials can be shared with researchers in toxicology, public health, and environmental science for evaluation before releasing them into society. These researchers can develop new measures and monitoring systems to continuously evaluate progress toward sustainability against the performance of other clean energy technologies. This collaboration gives chemists and engineers the feedback traditionally missing from the research and development phases of innovation. This mutually beneficial arrangement keeps evaluative researchers at the vanguard of their disciplines while also providing innovators with the feedback they need to create greener technologies.

Material selection for the design of photovoltaic technologies will determine much of their potential health and environmental impacts. These impacts include the consequences of material extraction, resource consumption, manufacturing processes, and end-of-life disposal or recycling. Each of these stages of production can result in occupational exposures and disproportionate impacts on nearby residential communities. It is crucial to evaluate progress early in the design cycle. For example, PV manufacturing currently requires the use of solvents and metals that are bioaccumulative, toxic, and environmentally persistent.[37,38] Based on similar technologies currently used in the semiconductor industry, PV manufacturing will generate new streams of hazardous waste and could replicate many of the occupational hazards of the electronics industry.[39,40] Photovoltaics, at the end of their lives, may create significant end-of-life waste problems unless recycling and disposal infrastructures are developed. It is important that principles of green chemistry are applied to the development of less toxic materials for use in PV systems. Some promising research is already occurring in this area, such as a new process for making thin solar cells with abundant materials that uses a nontoxic solvent.[41]

HOW INTERDISCIPLINARY COLLABORATION CAN IMPROVE: A VISION FOR THE FUTURE

Universities provide a setting in which high-risk but high-reward research and innovation can be done, whereas companies will usually be more limited in their research scope because of their market focus. To date, much green chemistry has largely consisted of first generation methods and tools that are developed within industries, such as efficient catalysts and safer solvents. The adoption of these first generation greener methods has been primarily driven by the economic benefits associated with reducing waste and increasing efficiency.[42] By contrast, universities are better placed to focus on fundamental research to invent the second and third generation technologies needed to address the grand challenges of sustainability.[7]

Increased interdisciplinary collaboration could improve green chemistry impacts, by moving from the current linear, one-directional process of developing technologies to an integrated, cycling process. In most existing chemical design and production activities, including green chemistry efforts, designers face discontinuous information flows regarding performance, environmental impact, and cost because of breakdowns in the product life cycle.[43] Product manufacturers rarely know about what environmental impacts occur during the use and disposal phases of the product life cycle, so they are unable to feed data about these impacts back into redesigning the product to reduce the impacts. In comparison, an interdisciplinary approach to green chemistry uses collaboration and integration between the various experts and actors to increase information flows along the product life cycle and feed data into repeating cycles of design based on learning about how the product performs and affects the environment.

Integrating green chemistry into chemistry education and research has occurred across the US, as seen in pioneering efforts at the University of Oregon, Carnegie Mellon University, and the University of Massachusetts at Boston. The annual Green Chemistry and Green Engineering conference has helped begin creating the missing venues for cross-disciplinary and cross-professional interactions. Nonetheless, funding from organizations like NSF and NIH could create more of these venues. Scholars from different disciplines could be partnered together in writing publications and grants, while tracks at disciplinary conferences could be created to attract other disciplinary viewpoints.

However, greater integration of multiple disciplines, including chemical sciences with social sciences, remains challenging. For example, in science, joint authorship is commonplace and expected, whereas in some social sciences, joint authorship is given lower priority than sole authorship. In universities, interdisciplinary research and teaching are often discouraged by the lack of institutional procedures for awarding credit for collaborative teaching, rewarding success in gaining grants involving several disciplines, or basing promotions on evidence of interdisciplinary problem-solving. These incentives could be introduced to make a university-wide commitment to innovative research management.

On a more epistemological level, disciplinary researchers need to be open to the contributions of other disciplines and accept that relevant expertise can take different forms. They need to willingly exchange views, listen carefully, and spend time explaining what may seem to be foolish questions.[14] All disciplines and subdisciplines can acknowledge honestly what they do not know and expose their norms and priorities for each other's scrutiny and mutual learning.[15]

In turn, chemists and social scientists can emphasize forming a research community around the green chemistry enterprise.[15] In contemporary natural and social sciences, disciplines are blurring together as researchers adopt models, methods, and concepts from each other (as seen in emerging integrated research models[44,45]). Rather than trying to overemphasize disciplinary boundaries, researchers can generate fruitful synergies from building a community around shared goals, topics, and the iterative R&D cycle.

This community-building can take the form of a collaborative entity such as the Berkeley Center for Green Chemistry (BCGC), founded in 2010 to increase contacts between disciplines. The BCGC includes policy, law, business, and environmental health research alongside chemistry. BCGC assures that disciplines share decision-making power with no single discipline prevailing, develops joint research grants, holds a collaborative research seminar, teaches interdisciplinary courses, and holds conferences that foster interdisciplinary dialogue.

Joint teaching programs promote continuous dialogue through designing and implementing courses.[46] For example, in spring 2011, BCGC-affiliated faculty taught Chemistry 234, an interdisciplinary course for 38 graduate students. Chemistry 234 interweaves law, policy, public health, chemistry, and business perspectives throughout the course. The course also uses interdisciplinary project teams to investigate topics that combine chemistry, policy, health, and business perspectives. Faculty from different disciplines coteach the classes and provide examples of interdisciplinary communication.

Students are essential to the process of creating more interdisciplinary research opportunities. For example, one student group in Chemistry 234 was asked to apply green chemistry principles to the challenge of cleaning up marine oil spills, following the Deepwater Horizon disaster in April 2010.[47] The toxicologists and environmental scientists in the group conducted a meta-analysis of the environmental impacts of various oil spill response techniques, not just dispersants. This supported meaningful alternatives analysis and drove the design of an integrative approach to oil spill response. The team produced an interactive spill response guide and characterized the need for new response technologies. In the end, the students identified the need for safer, more effective chemical dispersants, and for more comprehensive characterization of ecosystem services (e.g., provision of oil decomposition services by microbes, marine nutrient cycles supported by currents) to help evaluate the performance of different response options.

The students collaborated to write a critical review of oil response techniques and refine their own proposed response strategy. In addition to the review, the project stimulated successful joint proposals between chemistry and toxicology faculty to fund the design and synthesis of safer, more effective dispersants. Teams in the toxicology and chemistry laboratories are now working together to design and test these new surfactants on a small scale. From the classroom to the laboratory bench, the oil spill response project has engaged multiple disciplines and resulted in new research opportunities. Team members have begun to develop a shared language around green chemistry, using environmental science, ecology, and toxicology to develop a novel assessment framework and then using chemistry to develop new, safer molecules. While the policy, business, and social scientific aspects of developing oil response options remain underdeveloped, future student teams could build on this foundation to create a completely integrated research project.

No single model of interdisciplinary collaboration exists; we need experiments with different forms at many universities as part of new research for sustainability, including technologies such as green chemistry. In this case, chemists are increasingly not the only actors who are making decisions that influence the future sustainability of the chemical enterprise. Therefore, rather than maintaining the incremental course we are currently pursuing, we need an interdisciplinary approach that can fully realize green chemistry's transformative potential.

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Notes

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