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## Introduction: Reactivity of Nitrogen from the Ground to the Atmosphere

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Nitrogen is all around us as  $N_2$  in the atmosphere, but this nitrogen is often ignored by chemists interested in studying reactivity. Nitrogen usually seems unreactive, and thus Lavoisier named it *azote*, “no life.” Now, we know that the term *azote* is a misnomer, because all life is dependent on nitrogen atoms that are part of proteins, nucleic acids, and other biomolecules. The source of life-giving nitrogen is indeed atmospheric  $N_2$ , and there are organisms (diazotrophs) that can perform the mysterious and challenging reactions that “fix”  $N_2$  to produce ammonia. However, this biological nitrogen fixation is insufficient to meet the nutritional needs of the world’s current population, and requires an anthropogenic supplement through the industrial Haber-Bosch process, which gives a synthetic source of fertilizers. The modern story of nitrogen is also more than just ammonia: society of the 21st century depends on a diverse cast of nitrogen-containing molecules that fulfill critical roles in pharmaceuticals, polymers, propellants, dyes, and catalysts. Perhaps Lavoisier would have stuck out his neck more when naming it, if he had known where *azote* would be headed!

Nitrogen has been a key topic of research in the chemistry, chemical engineering, geology, and biology communities for more than a century. It promises to be an even more active area of research in the future, as scientists increasingly focus on nontoxic resources that are abundant on a global scale. For instance, the interconversion of  $N_2$  with  $NH_3$  is envisioned as the basis of a system for chemical energy storage, because ammonia is a carbon-free liquid fuel for which the engineering challenges of storage and distribution have already been addressed in the context of fertilizers. In addition, nitrogen’s many other uses will continue to multiply as chemists develop new functional materials with nitrogen-containing components.

This Thematic Issue of *Chemical Reviews* compiles, categorizes, and critically assesses important aspects of nitrogen chemistry, with a special focus on  $N_2$ . Research leaders in different areas of nitrogen chemistry generously contributed their time and effort to complementary reviews that will help the community to assess the status of knowledge and the opportunities for new research. I hope that the Thematic Issue helps readers to see the breadth of nitrogen research, and to celebrate the many innovative strategies that have been brought to bear on the challenges of understanding nitrogen.

In keeping with the atomic number of nitrogen, 7 of the reviews cover aspects of the enzymes that reduce  $N_2$  in nature, which are known as nitrogenases. The study of

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nitrogenases has served as one of the most grueling testing grounds of bioinorganic chemistry, and has inspired the development of new tools and new concepts that are discussed in these reviews. Nitrogenases feature a set of unique iron-sulfur clusters, which are generated in natural systems using a complicated biomolecular machinery that is reviewed by Burén, Jiménez-Vicente, Echavarrí-Erasum, and Rubio. The structures of the resulting cofactors, and the surrounding protein architectures, are reviewed by Einsle and Rees. These structural studies provide insight into the mechanism of nitrogenases, which remains an area of controversy that is discussed from different perspectives in the various nitrogenase reviews. New advances in understanding mechanism require data from spectroscopic studies, which are reviewed by Van Stappen, Decamps, Cutsail, Björnsson, Henthorn, Birrell, and DeBeer. Though their job is to reduce  $N_2$ , nitrogenases also reduce numerous other small molecules, and the mechanistic insights arising from the various substrates are reviewed by Seefeldt, Yang, Lukoyanov, Harris, Dean, Raugei, and Hoffman. There are many emerging differences in reactivity between Mo-nitrogenase and the “alternative nitrogenases,” V-nitrogenase and Fe-only nitrogenase, which are reviewed by Jasiewicz, Lee, Ribbe, and Hu. Movement of electrons must be carefully coordinated during reduction of substrates, and Rutledge and Tezcan review the details of electron transfer in the nitrogenases. The structures and the mechanisms of the key iron-sulfur clusters in nitrogenases require new concepts in fundamental coordination chemistry, and the review of Tanifuji and Ohki describes synthetic iron-sulfur clusters and related sulfide materials that aid mechanistic thinking by providing structural and/or reactivity models for the nitrogenases.

Natural systems do not only cleave N–N bonds: they also form N–N bonds through the action of metalloenzymes. Ferousi, Majer, DiMucci, and Lancaster review the mechanisms of enzymes that form  $N_2$ , as well as enzymes that involve other molecules containing N–N bonds like  $N_2O$  (nitrous oxide) and  $N_2H_4$  (hydrazine). The formation and consumption of all of these small molecules in the environment constitutes the global nitrogen cycle, which describes the flow of nitrogen atoms through various environments and is reviewed by Zhang, Ward, and Sigman. Chemists have recognized that nitrogen redox has promise for carbon-free chemical energy storage using abundant nitrogen atoms, and the prospects for various nitrogen-based alternative fuel schemes are reviewed by Elishav, Mosevitzky Lis, Miller, Arent, Valera-Medina, Grinberg Dana, Shter, and Grader. An emerging strategy for capturing energy in nitrogen is through the electrochemical reduction of  $N_2$  to ammonia, a rapidly emerging field that is reviewed by Qing, Ghazfar, Jackowski, Habibzadeh, Ashtiani, Chen, Smith, and Hamann.

Metal species catalyze all of the above interconversions, and understanding the inorganic reaction mechanisms requires fundamental knowledge about how metal complexes interact with  $N_2$ . One emerging trend is the use of cooperative interactions with multiple transition metals to enhance the binding and cleavage of  $N_2$ , which is reviewed by Singh, Buratto, Torres Gonzalez, and Murray. One of the most exciting advances in recent years is the identification of synthetic complexes that accomplish the catalytic reduction of  $N_2$  to ammonia, and these are reviewed by Chalkley, Drover, and Peters. Chemists also strive to form organic compounds from  $N_2$ , and Kim, Loose, and Chirik review the progress in this

area that will enable chemists to use abundant  $N_2$  as a raw material for the synthesis of pharmaceuticals and other nitrogen-containing chemicals.

Though this issue has a predominant focus on  $N_2$ , there are other fascinating aspects of nitrogen chemistry that are under active development, and no Thematic Issue on lucky element 7 would be complete without them. Compounds with chains of N–N bonds are electronically interesting and thermodynamically unstable, and their properties as propellants and explosives are reviewed by O’Sullivan and Zdilla. In another topic, nitrogen incorporation into the network structure of diamond gives novel properties of interest to various fields from geophysics to quantum computing, and this topic is reviewed by Ashfold, Goss, Green, May, Newton, and Peaker. Overall, the diverse set of review articles in this Thematic Issue shows that no matter what Lavoisier might have thought, nitrogen is an element that will be lively for many years to come.

I close this introduction by gratefully acknowledging those without whom this issue would not have come to pass. First and foremost, I thank the authors who put forward the gargantuan efforts needed to amass these comprehensive reviews. I was amazed at the enthusiasm with which the authors agreed to undertake this arduous task. I also thank the referees who, without credit, were willing to put in the large amount of time it takes to critically refine the review articles for the highest quality, organization, and accuracy. I would also like to thank Guy Bertrand and Michele Soleilhavoup-Bertrand at *Chemical Reviews* for handling the papers and the referee reports, for keeping the review process speedy, and for protecting me from having to make editorial decisions on papers. Finally, I would like to thank my research group at Yale for helping to brainstorm ideas, with special commendations to Kazimer Skubi for coming up with the issue title (as well as excellent alternatives such as “Vanishing  $N_2$  Thin Air” and “Just  $N_2$  of us: we can make it if we try”), and Alexandra Nagelski for designing and drawing the cover illustration.

## Biography



Patrick Holland received his Bachelor of Arts from Princeton University and Ph.D. from the University of California at Berkeley, studying organometallic chemistry with Richard Andersen and Robert Bergman. He then chose to move into bioinorganic chemistry, through postdoctoral research with William Tolman at the University of Minnesota. From 2000 to 2013, he was on the faculty at the University of Rochester, where he established a research program on low-coordinate coordination compounds and organometallic chemistry, with a special focus on  $N_2$  fixation by iron complexes. In 2013, he moved to Yale University, where he is Professor of Chemistry. His current research interests include reactive complexes with low coordination numbers and/or redox-active ligands, mechanistic organometallic chemistry with emphasis on transformations of alkenes with inexpensive metals, the binding,

reduction, and functionalization of  $N_2$  including nitrogenase modeling, and the development of catalysts that transform molecules with energy from light.

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