



**Cover image:** Pictured is a mantis shrimp (*Neogonodactylus oerstedi*). Megan L. Porter et al. examined *N. oerstedi* retinal tissue and found that 33 opsin transcripts are expressed in the shrimp's eyes, including an opsin expressed in all color receptors. The retinal tissue also contains single photoreceptors that coexpress opsins from different spectral clades. The shrimp's opsin transcripts form visual pigments that are sensitive to ultraviolet light as well as middle-wavelength and long-wavelength light. Unexpected opsin retinal expression patterns in *N. oerstedi* suggest the potential for cryptic photoreceptor functional diversity. See the article by Porter et al. on pages 8948–8957. Image credit: Roy L. Caldwell (University of California, Berkeley, CA).

## From the Cover

- 8948 Mantis shrimp visual gene expression
- 8743 Carbon reserve in Earth's core
- 8804 Curbing pollution with carbon markets
- 9101 Cytosolic protein and photoautotrophic growth
- 9122 Hospital capacity during COVID-19 outbreak

## Contents

### THIS WEEK IN PNAS

- 8661 In This Issue

### OPINION—Leading scientists discuss current issues

- 8664 Why carbon pricing is not sufficient to mitigate climate change—and how “sustainability transition policy” can help  
*Daniel Rosenbloom, Jochen Markard, Frank W. Geels, and Lea Fuenfschilling*

### COMMENTARIES

- 8669 Identifying the pathways that control resource allocation in higher plants  
*Daniel R. Bush*  
→ See companion article on page 6223 in issue 11 of volume 117
- 8672 From photosynthesis to photocatalysis: Dual catalytic oxidation/reduction in one system  
*Lin X. Chen*  
→ See companion article on page 6376 in issue 12 of volume 117
- 8674 Protein conformations à la carte, a step further in de novo protein design  
*Faruck Morcos*  
→ See companion article on page 7208 in issue 13 of volume 117
- 8677 On the enigma of dating the Minoan eruption of Santorini  
*Walter Kutschera*  
→ See companion article on page 8410 in issue 15 of volume 117
- 8680 The role of the iterative modules in polyketide synthase evolution  
*Martin Grininger*  
→ See companion article on page 8449 in issue 15 of volume 117

### PERSPECTIVE

- 8683 Earth 2020: Science, society, and sustainability in the Anthropocene  
 *Philippe D. Tortell*

### LETTERS

- 8692 The phylogenetic tree of boosting has a bushy carriage but a single trunk  
 *Richard Nock and Frank Nielsen*

- 8694** **Reply to Nock and Nielsen: On the work of Nock and Nielsen and its relationship to the additive tree**  
Gilmer Valdes, José Marcio Luna, Efstathios D. Gennat, Lyle H. Ungar, Eric Eaton, Eric S. Diffenderfer, Shane T. Jensen, Charles B. Simone II, Jerome H. Friedman, and Timothy D. Solberg
- 8696** **Replications provide mixed evidence that inequality moderates the association between income and generosity**  
Stéphane Côté and Robb Willer
- 8698** **Reply to Côté and Willer: New replication attempts provide no evidence that inequality moderates the effect of income on generosity**  
Stefan C. Schmukle and Boris Egloff
- 
- PHYSICAL SCIENCES**
- APPLIED PHYSICAL SCIENCES**
- 8700** **Scale-free, programmable design of morphable chain loops of kilobots and colloidal motors**  
Mayank Agrawal and Sharon C. Glotzer
- BIOPHYSICS AND COMPUTATIONAL BIOLOGY**
- 8711** **Actuation and locomotion driven by moisture in paper made with natural pollen**  
Ze Zhao, Youngkyu Hwang, Yun Yang, Tengfei Fan, Juha Song, Subra Suresh, and Nam-Joon Cho
- 8719** **Computational design of probes to detect bacterial genomes by multivalent binding**  
Tine Cerk, Chris A. Brackley, James D. Farrell, Zhongyang Xing, Darshana Joshi, Susana Direito, Urban Bren, Stefano Angioletti-Uberti, Jure Dobnikar, Erika Eiser, Daan Frenkel, and Rosalind J. Allen
- 8934** **A model for the interplay between plastic tradeoffs and evolution in changing environments**  
Mikhail Tikhonov, Shamit Kachru, and Daniel S. Fisher
- CHEMISTRY**
- 8727** **Ultratough graphene–black phosphorus films**  
Tianzhu Zhou, Hong Ni, Yanlei Wang, Chao Wu, Hao Zhang, Jianqi Zhang, Antoni P. Tomśia, Lei Jiang, and Qunfeng Cheng
- 8736** **Pressure-induced amorphization and existence of molecular and polymeric amorphous forms in dense SO<sub>2</sub>**  
Huchao Zhang, Ondrej Tóth, Xiao-Di Liu, Roberto Bini, Eugene Gregoryanz, Philip Dalladay-Simpson, Simone De Panfilis, Mario Santoro, Federico Aiace Gorelli, and Roman Martoňák
- EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES**
- 8743** **The carbon content of Earth and its core**  
Rebecca A. Fischer, Elizabeth Cottrell, Erik Hauri, Kanani K. M. Lee, and Marion Le Voyer
- 8750** **Depth-dependent soil mixing persists across climate zones**  
Harrison J. Gray, Amanda Keen-Zebert, David J. Furbish, Gregory E. Tucker, and Shannon A. Mahan
- 8757** **Dry and moist dynamics shape regional patterns of extreme precipitation sensitivity**  
Ji Nie, Panxi Dai, and Adam H. Sobel
- ENGINEERING**
- 8764** **Multifunctional composites for elastic and electromagnetic wave propagation**  
Jaeuk Kim and Salvatore Torquato
- 
- ENVIRONMENTAL SCIENCES**
- 8989** **The spatiotemporal spread of human migrations during the European Holocene**  
Fernando Racimo, Jessie Woodbridge, Ralph M. Fyfe, Martin Sikora, Karl-Göran Sjögren, Kristian Kristiansen, and Marc Vander Linden
- PHYSICS**
- 8775** **Signature of a pair of Majorana zero modes in superconducting gold surface states**  
Sujit Manna, Peng Wei, Yingming Xie, Kam Tuen Law, Patrick A. Lee, and Jagadeesh S. Moodera
- 8783** **Room-temperature skyrmion phase in bulk Cu<sub>2</sub>OSeO<sub>3</sub> under high pressures**  
Liangzi Deng, Hung-Cheng Wu, Alexander P. Litvinchuk, Noah F. Q. Yuan, Jey-Jau Lee, Rabin Dahal, Helmut Berger, Hung-Duen Yang, and Ching-Wu Chu
- 8788** **Coherent modulation of the electron temperature and electron–phonon couplings in a 2D material**  
Yingchao Zhang, Xun Shi, Wenjing You, Zhenheng Tao, Yigui Zhong, Fairoja Cheenicode Kabeer, Pablo Maldonado, Peter M. Oppeneer, Michael Bauer, Kai Rossnagel, Henry Kapteyn, and Margaret Murnane
- 
- SOCIAL SCIENCES**
- ECONOMIC SCIENCES**
- 8794** **The impact of penalties for wrong answers on the gender gap in test scores**  
Katherine B. Coffman and David Klinowski
- ENVIRONMENTAL SCIENCES**
- 8804** **The European Union Emissions Trading System reduced CO<sub>2</sub> emissions despite low prices**  
Patrick Bayer and Michaël Aklin
- 8813** **Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought**  
David A. Sear, Melinda S. Allen, Jonathan D. Hassall, Ashley E. Maloney, Peter G. Langdon, Alex E. Morrison, Andrew C. G. Henderson, Helen Mackay, Ian W. Croudace, Charlotte Clarke, Julian P. Sachs, Georgiana Macdonald, Richard C. Chiverrell, Melanie J. Leng, L. M. Cisneros-Doval, and Thierry Fonville
- PSYCHOLOGICAL AND COGNITIVE SCIENCES**
- 8820** **Inconsistent allocations of harms versus benefits may exacerbate environmental inequality**  
Tamar Makov, George E. Newman, and Gal Zauberman
- 8825** **Scaling up psychology via Scientific Regret Minimization**  
Mayank Agrawal, Joshua C. Peterson, and Thomas L. Griffiths
- SOCIAL SCIENCES**
- 8836** **Latinos' deportation fears by citizenship and legal status, 2007 to 2018**  
Asad L. Asad
- 
- BIOLOGICAL SCIENCES**
- APPLIED BIOLOGICAL SCIENCES**
- 8711** **Actuation and locomotion driven by moisture in paper made with natural pollen**  
Ze Zhao, Youngkyu Hwang, Yun Yang, Tengfei Fan, Juha Song, Subra Suresh, and Nam-Joon Cho

	<b>BIOCHEMISTRY</b>		
8845	<b>Expanding the genetic code of the human hematopoietic system</b> Sida Shao, Minsoob Koh, and Peter G. Schultz	8958	<b>Convergent evolution of olfactory and thermoregulatory capacities in small amphibious mammals</b> Quentin Martinez, Julien Clavel, Jacob A. Esselstyn, Anang S. Achmadi, Camille Grohé, Nelly Pirot, and Pierre-Henri Fabre
8850	<b>Reconstitution of polythioamide antibiotic backbone formation reveals unusual thiotemplated assembly strategy</b> Kyle L. Dunbar, Maria Dell, Finn Gude, and Christian Hertweck	8966	<b>Aquatic stem group myriapods close a gap between molecular divergence dates and the terrestrial fossil record</b> Gregory D. Edgecombe, Christine Strullu-Derrien, Tomasz Góral, Alexander J. Hetherington, Christine Thompson, and Markus Koch
8859	<b>CtIP promotes the motor activity of DNA2 to accelerate long-range DNA end resection</b> Ilaria Ceppi, Sean M. Howard, Kristina Kasaciunaite, Cosimo Pinto, Roopesh Anand, Ralf Seidel, and Petr Cejka	8973	<b>Trade-off between somatic and germline repair in a vertebrate supports the expensive germ line hypothesis</b> Hwei-yan Chen, Cecile Jolly, Kasparas Bublys, Daniel Marcu, and Simone Immler
	<b>BIOPHYSICS AND COMPUTATIONAL BIOLOGY</b>		
8870	<b>Modular repeat protein sculpting using rigid helical junctions</b> TJ Brunette, Matthew J. Bick, Jesse M. Hansen, Cameron M. Chow, Justin M. Kollman, and David Baker	8980	<b>Derived alleles of two axis proteins affect meiotic traits in autotetraploid <i>Arabidopsis arenosa</i></b> Chris Morgan, Huakun Zhang, Clare E. Henry, F. Chris H. Franklin, and Kirsten Bomblies
8876	<b>Tubulin tails and their modifications regulate protein diffusion on microtubules</b> Lavi S. Bigman and Yaakov Levy		
8884	<b>Kinetic control of stationary flux ratios for a wide range of biochemical processes</b> Joel D. Mallory, Anatoly B. Kolomeisky, and Oleg A. Igoshin		
8890	<b>Cryo-EM structure of eastern equine encephalitis virus in complex with heparan sulfate analogues</b> Chun-Liang Chen, S. Saif Hasan, Thomas Klose, Yingyuan Sun, Geeta Buda, Chengqun Sun, William B. Klimstra, and Michael G. Rossmann		
	<b>CELL BIOLOGY</b>		<b>GENETICS</b>
8900	<b>Aminoacyl-tRNA synthetase inhibition activates a pathway that branches from the canonical amino acid response in mammalian cells</b> Yeonjin Kim, Mark S. Sundrud, Changqian Zhou, Maja Edeniuk, Davide Zocco, Kristen Powers, Miao Zhang, Ralph Mazitschek, Anjana Rao, Chang-Yeol Yeo, Erika H. Noss, Michael B. Brenner, Malcolm Whitman, and Tracy L. Keller	8989	<b>The spatiotemporal spread of human migrations during the European Holocene</b> Fernando Racimo, Jessie Woodbridge, Ralph M. Fyfe, Martin Sikora, Karl-Göran Sjögren, Kristian Kristiansen, and Marc Vander Linden
8912	<b>Primary cilia control glucose homeostasis via islet paracrine interactions</b> Jing W. Hughes, Jung Hoon Cho, Hannah E. Conway, Michael R. DiGruccio, Xue Wen Ng, Henry F. Roseman, Damien Abreu, Fumihiro Urano, and David W. Piston	9001	<b>Mapping the cis-regulatory architecture of the human retina reveals noncoding genetic variation in disease</b> Timothy J. Cherry, Marty G. Yang, David A. Harmin, Peter Tao, Andrew E. Timms, Miriam Bauwens, Rando Allikmets, Evan M. Jones, Rui Chen, Elfride De Baere, and Michael E. Greenberg
8924	<b>Hog1 activation delays mitotic exit via phosphorylation of Net1</b> Silvia Tognetti, Javier Jiménez, Matteo Viganò, Alba Duch, Ethel Queralt, Eulàlia de Nadal, and Francesc Posas	9013	<b>Gene drive and resilience through renewal with next generation Cleave and Rescue selfish genetic elements</b> Georg Oberhofer, Tobin Ivy, and Bruce A. Hay
	<b>EVOLUTION</b>	9022	<b>The T1D-associated lncRNA Lnc13 modulates human pancreatic <math>\beta</math> cell inflammation by allele-specific stabilization of STAT1 mRNA</b> Itzíar Gonzalez-Moro, Ane Olazagoitia-Garmendia, Maikel L. Colli, Nadia Cobo-Vuilleumier, Thomas S. Postler, Lorella Marselli, Piero Marchetti, Sankar Ghosh, Benoit R. Gauthier, Decio L. Eizirik, Ainara Castellanos-Rubio, and Izortze Santin
8934	<b>A model for the interplay between plastic tradeoffs and evolution in changing environments</b> Mikhail Tikhonov, Shamit Kachru, and Daniel S. Fisher	9032	<b>Cell-autonomous expression of the acid hydrolase galactocerebrosidase</b> Christina R. Mikulka, Joshua T. Dearborn, Bruno A. Benitez, Amy Strickland, Lin Liu, Jeffrey Milbrandt, and Mark S. Sands
8941	<b>Bacterial flagellar motor PL-ring disassembly subcomplexes are widespread and ancient</b> Mohammed Kaplan, Michael J. Sweredoski, João P. G. L. M. Rodrigues, Elitza I. Tocheva, Yi-Wei Chang, Davi R. Ortega, Morgan Beeby, and Grant J. Jensen	9042	<b>Noncoding RNA <i>Mall1</i> is an integral component of the TLR4-TRIF pathway</b> Marina Aznaourova, Harshavardhan Janga, Stephanie Sefried, Andreas Kaufmann, Jens Dorna, Sarah M. Volkers, Philipp Georg, Marcus Lechner, Judith Hoppe, Simon Dökel, Nils Schmerer, Achim D. Gruber, Uwe Linne, Stefan Bauer, Leif E. Sander, Bernd Schmeck, and Leon N. Schulte
8948	<b>Exceptional diversity of opsin expression patterns in <i>Neogonodactylus oerstedi</i> (<i>Stomatopoda</i>) retinas</b> Megan L. Porter, Hiroko Awata, Michael J. Bok, and Thomas W. Cronin	9054	<b>Combined proinflammatory cytokine and cognate activation of invariant natural killer T cells enhances anti-DNA antibody responses</b> Saikiran K. Sedimbi, Thomas Hägglöf, Manasa G. Garimella, Shan Wang, Amanda Duhlin, Ana Coelho, Katrine Ingelshed, Emma Mondoc, Stephen G. Malin, Rikard Holmdahl, David P. Lane, Elizabeth A. Leadbetter, and Mikael C. I. Karlsson

**MEDICAL SCIENCES**

- 9064** PHIP drives glioblastoma motility and invasion by regulating the focal adhesion complex  
David de Semir, Vladimir Bezrookove, Mehdi Nosrati, Kara R. Scanlon, Eric Singer, Jonathon Judkins, Christopher Rieken, Clayton Wu, Julia Shen, Christina Schmudermayer, Altaf A. Dar, James R. Miller III, Charles Cobbs, Garret Yount, Pierre-Yves Desprez, Robert J. Debs, Nathan Salomonis, Sean McAllister, James E. Cleaver, Liliana Soroceanu, and Mohammed Kashani-Sabet

**MICROBIOLOGY**

- 9074** A common polymorphism in the mechanosensitive ion channel PIEZO1 is associated with protection from severe malaria in humans  
Christian N. Nguetse, Natasha Purington, Emily R. Ebel, Bikash Shakya, Marilou Tetard, Peter G. Kremsner, Thirumalaivasamy P. Velavan, and Elizabeth S. Egan

**NEUROSCIENCE**

- 9082** A dual effect of ursolic acid to the treatment of multiple sclerosis through both immunomodulation and direct remyelination  
Yuan Zhang, Xing Li, Bogoljub Ceric, Mark T. Curtis, Wan-Jun Chen, Abdolmohamad Rostami, and Guang-Xian Zhang
- 9094** Activity in grafted human iPS cell-derived cortical neurons integrated in stroke-injured rat brain regulates motor behavior  
Sara Palma-Tortosa, Daniel Tornero, Marita Grønning Hansen, Emanuela Monni, Mazin Hajj, Sopiko Kartsivadze, Sibel Aktay, Oleg Tsypukov, Malin Parmar, Karl Deisseroth, Galyna Skibo, Olle Lindvall, and Zaal Kokaia

**PLANT BIOLOGY**

- 9101** A Sec14 domain protein is required for photoautotrophic growth and chloroplast vesicle formation in *Arabidopsis thaliana*  
Alexander P. Hertle, José G. García-Cerdán, Ute Armbruster, Robert Shih, Jimmy J. Lee, Winnie Wong, and Krishna K. Niyogi
- 9112** Distinct modes of manipulation of rice auxin response factor OsARF17 by different plant RNA viruses for infection  
Hehong Zhang, Lulu Li, Yuqing He, Qingqing Qin, Changhai Chen, Zhongyan Wei, Xiaoxiang Tan, Kaili Xie, Ruifang Zhang, Gaojie Hong, Jing Li, Junmin Li, Chengqi Yan, Fei Yan, Yi Li, Jianping Chen, and Zongtao Sun

**POPULATION BIOLOGY**

- 9122** Projecting hospital utilization during the COVID-19 outbreaks in the United States  
Seyed M. Moghadas, Affan Shoukat, Meagan C. Fitzpatrick, Chad R. Wells, Pratha Sah, Abhishek Pandey, Jeffrey D. Sachs, Zheng Wang, Lauren A. Meyers, Burton H. Singer, and Alison P. Galvani

**CORRECTION****PSYCHOLOGICAL AND COGNITIVE SCIENCES**

- 9127** Officer characteristics and racial disparities in fatal officer-involved shootings  
David J. Johnson, Trevor Tress, Nicole Burkel, Carley Taylor, and Joseph Cesario