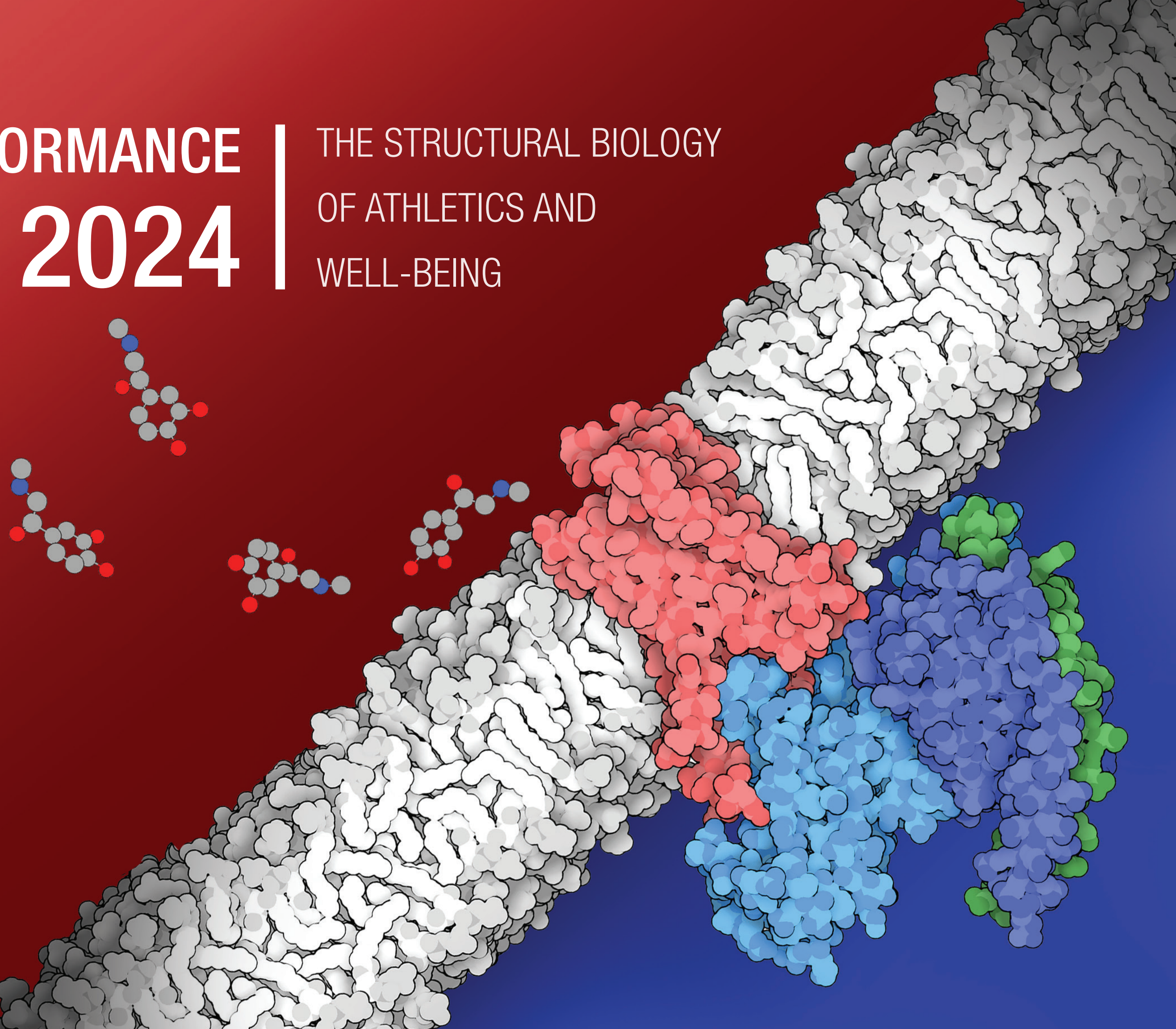
PEAK PERFORMANCE FOR 2024

THE STRUCTURAL BIOLOGY OF ATHLETICS AND WELL-BEING



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PEAK PERFORMANCE: THE STRUCTURAL BIOLOGY OF ATHLETICS AND WELL-BEING

Athletes require bodies that perform best, all the way from molecules to muscles. By understanding the structure and function of biomolecules, athletes can ensure that they are performing at their peak. These include molecules that power and control muscle action, molecules that turn food into energy, essential dietary molecules that are required for health, and molecules that protect our bodies under extreme stress and exertion. This knowledge also informs the ways that all of us can live our best lives, at all stages of our lives.

Images in this calendar are based on structural data from the Protein Data Bank. Visit **RCSB.org** and use the PDB IDs provided here to explore the proteins in 3D.

To learn more, go to **pdb101.rcsb.org** and visit the category *Browse > Health and Disease > Peak Performance* or scan the code.

Molecular images were created using

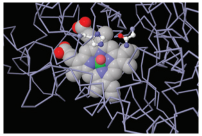
Chimera: E.F. Pettersen *et al.* (2004) *J Comput Chem* **25**: 1605-1612.

Illustrate: D.S. Goodsell, L. Autin, A.J. Olson (2019) *Structure* **27**: 1716-1720.

Jmol: an open-source Java viewer for chemical structures in 3D. www.jmol.org.

mMaya (Molecular Maya): a plugin for Autodesk Maya available at clarafi.com.

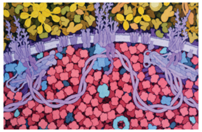
Mol* (Molstar): available for 3D visualization on RCSB.org. D. Sehnal *et al.* (2021) *Nucleic Acids Research* **49**: W431-W437.



JANUARY | **Catalase**

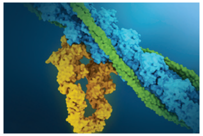
PDB ID 2cag Ferryl intermediates of catalase captured by time-resolved Weissenberg crystallography and UV-VIS spectroscopy. P. Gouet, H.M. Jouve, P.A. Williams, I. Andersson, P. Andreoletti, L. Nussaume, J. Hajdu (1996) *Nat Struct Biol* **3**: 951-956.

Jmol image designed by Belle Lin sourced from September 2004 *Molecule of the Month* on *Catalase.*



FEBRUARY | **Hemoglobin**

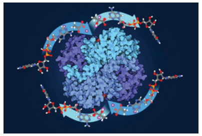
Illustration by David S. Goodsell, RCSB Protein Data Bank. https://doi.org/10.2210/rcsb_pdb/goodsell-gallery-031



MARCH | **Myosin**

PDB ID 7nep The molecular basis for sarcomere organization in vertebrate skeletal muscle. Z. Wang, M. Grange, T. Wagner, A.L. Kho, M. Gautel, S. Raunser (2021) *Cell* **184**: 2135-2150.

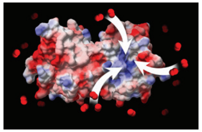
Molecular image created using mMaya.



JULY | **Lactate Dehydrogenase**

PDB ID 3ldh A comparison of the structures of apo dogfish M4 lactate dehydrogenase and its ternary complexes. J.L. White, M.L. Hackert, M. Buehner, M.J. Adams, G.C. Ford, P.J. Lentz Jr., I.E. Smiley, S.J. Steindel, M.G. Rossmann (1976) *J Mol Biol* **102**: 759-779.

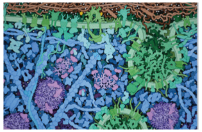
Lactate dehydrogenase image created with Illustrate sourced from June 2008 *Molecule of the Month*. Images of small molecules created with Chimera.



AUGUST | **Superoxide Dismutase**

PDB ID 2sod Determination and analysis of the 2 Å-structure of copper, zinc superoxide dismutase. J.A. Tainer, E.D. Getzoff, K.M. Beem, J.S. Richardson, D.C. Richardson (1982) *J Mol Biol* **160**: 181-217.

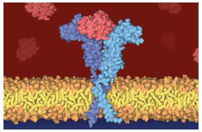
Molecular image created using Chimera.



SEPTEMBER | **Glycogen**

Illustration by David S. Goodsell, RCSB Protein Data Bank. https://doi.org/10.2210/rcsb_pdb/goodsell-gallery-014

APRIL | **Growth Hormone**

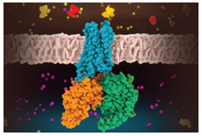


PDB ID 5oek Structural basis of the signal transduction via transmembrane domain of the human growth hormone receptor. E.V. Bocharov, D.M. Lesovoy, O.V. Bocharova, A.S. Urban, K.V. Pavlov, P.E. Volynsky, R.G. Efremov, A.S. Arseniev (2018) *Biochim Biophys Acta* **1862**: 1410-1420.e6.

Lipid bilayer image created from **PDB ID 6clz** MT1-MMP Binds Membranes by Opposite Tips of Its beta Propeller to Position It for Pericellular Proteolysis. T.C. Marcink, J.A. Simoncic, B. An, A.M. Knapinska, Y.G. Fulcher, N. Akkaladevi, G.B. Fields, S.R. Van Doren (2019) *Structure* **27**: 281-292.

Protein/membrane complex image created using Illustrate.

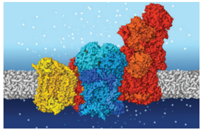
MAY | **Opioid Receptor**



PDB ID 6dde Structure of the mu-opioid receptor-Gi protein complex. A. Koehl, H. Hu, S. Maeda, Y. Zhang, Q. Qu, J.M. Paggi, N.R. Latorraca, D. Hilger, R. Dawson, H. Matile, G.F.X. Schertler, S. Granier, W.I. Weis, R.O. Dror, A. Manglik, G. Skiniotis, B.K. Kobilka (2018) *Nature* **558**: 547-552.

Frame from PDB-101 video *Opioids and Pain Signaling*.
Molecular model created with mMaya.

JUNE | **Respiratory Supercomplex**

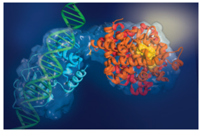


PDB ID 5xth Architecture of Human Mitochondrial Respiratory Megacomplex I2III2IV2. R. Guo, S. Zong, M. Wu, J. Gu, M. Yang (2017) *Cell* **170**: 1247-1257.e12.

Lipid bilayer image created from **PDB ID 6clz** *(see April citation).*

Molecular image created with Mol*.

OCTOBER | **Vitamin D Receptor**



PDB ID 1dkf Crystal structure of a heterodimeric complex of RAR and RXR ligand-binding domains. W. Bourguet, V. Vivat, J. M. Wurtz, P. Chambon, H. Gronemeyer, D. Moras (2000) *Mol Cell* **5**: 289-298.

PDB ID 1db1 The crystal structure of the nuclear receptor for vitamin D bound to its natural ligand. N. Rochel, J. M. Wurtz, A. Mitschler, B. Klaholz, D. Moras (2000) *Mol Cell* **5**: 173-179.

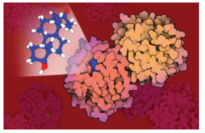
PDB ID 2nll Structural determinants of nuclear receptor assembly on DNA direct repeats F. Rastinejad, T. Perlmann, R. M. Evans, P. B. Sigler (1995) *Nature* **375**: 203-211.

PDB ID 1ynw Structural analysis of RXR-VDR interactions on DR3 DNA. P. L. Shaffer, D. T. Gewirth (2004) *J Steroid Biochem Mol Biol* **89-90**: 215-219.

EMD-1985 Structure of the full human RXR/VDR nuclear receptor heterodimer complex with its DR3 target DNA. I. Orlov, N. Rochel, D. Moras, B. P. Klaholz (2012) *EMBO J* **31**: 291-293.

Molecular image created with Chimera.

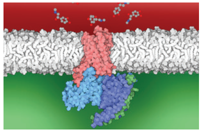
NOVEMBER | **Anabolic Steroids**



PDB ID 1d2s Crystal structure of human sex hormone-binding globulin: steroid transport by a laminin G-like domain. I. Grishkovskaya, G.V. Avvakumov, G. Sklenar, D. Dales, G.L. Hammond, Y.A. Muller (2000) *EMBO J* **19**: 504-512.

Image source: August 2007 *Molecule of the Month* on *Anabolic Steroids*. Image of protein created with Illustrate. Image of testosterone created with Chimera.

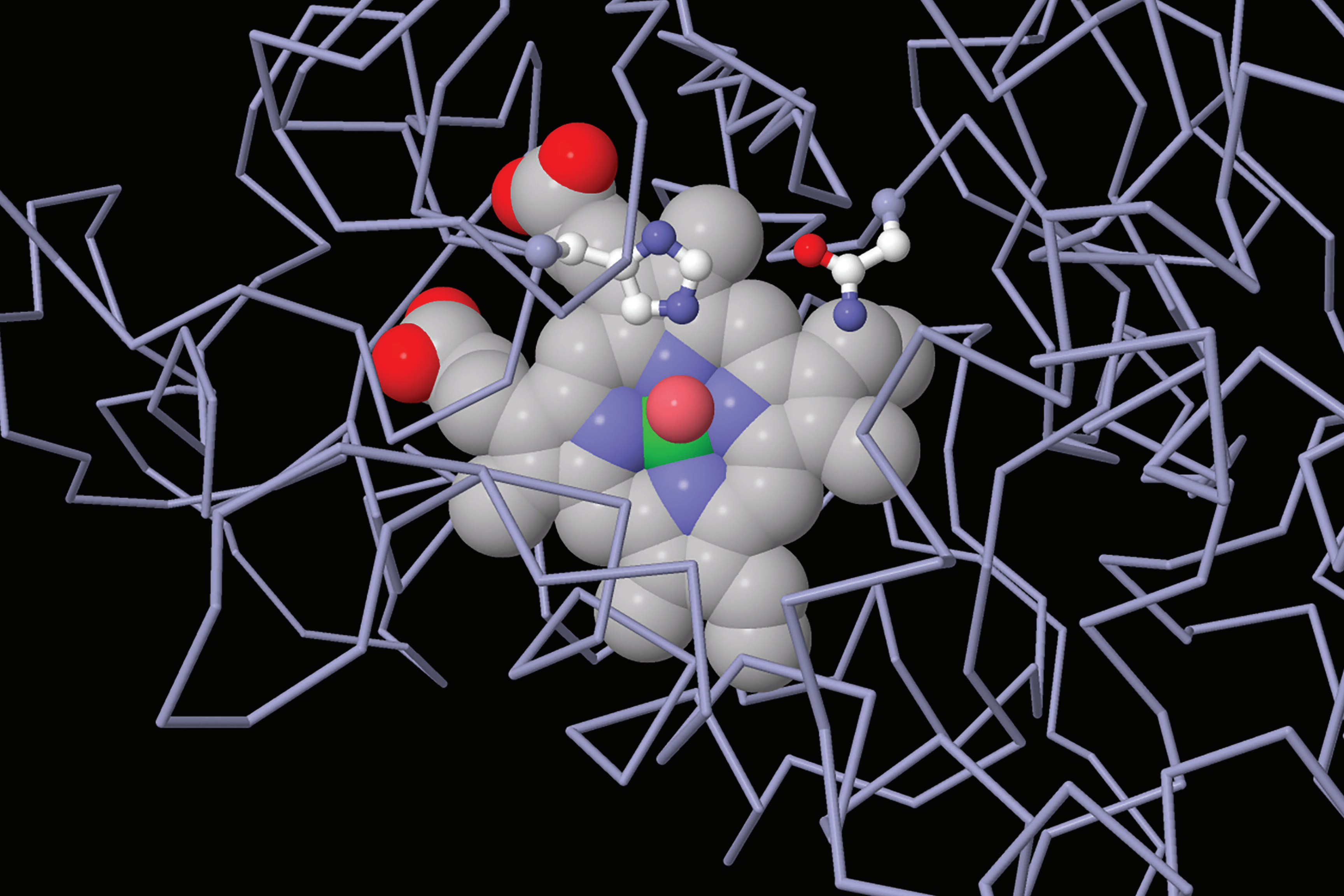
DECEMBER | **Beta-2 Adrenergic Receptor**



PDB ID 3sn6 Crystal structure of the beta2 adrenergic receptor-Gs protein complex S.G. Rasmussen, B.T. DeVree, Y. Zou, A.C. Kruse, K.Y. Chung, T.S. Kobilka, F.S. Thian, P.S. Chae, E. Pardon, D. Calinski, J.M. Mathiesen, S.T. Shah, J.A. Lyons, M. Caffrey, S.H. Gellman, J. Steyaert, G. Skiniotis, W.I. Weis, R.K. Sunahara, B.K. Kobilka (2011) *Nature* **477**: 549-555.

Lipid bilayer image created from **PDB ID 6clz** *(see April citation).*

Protein/membrane complex image created using Illustrate, image of adrenaline created with Chimera.



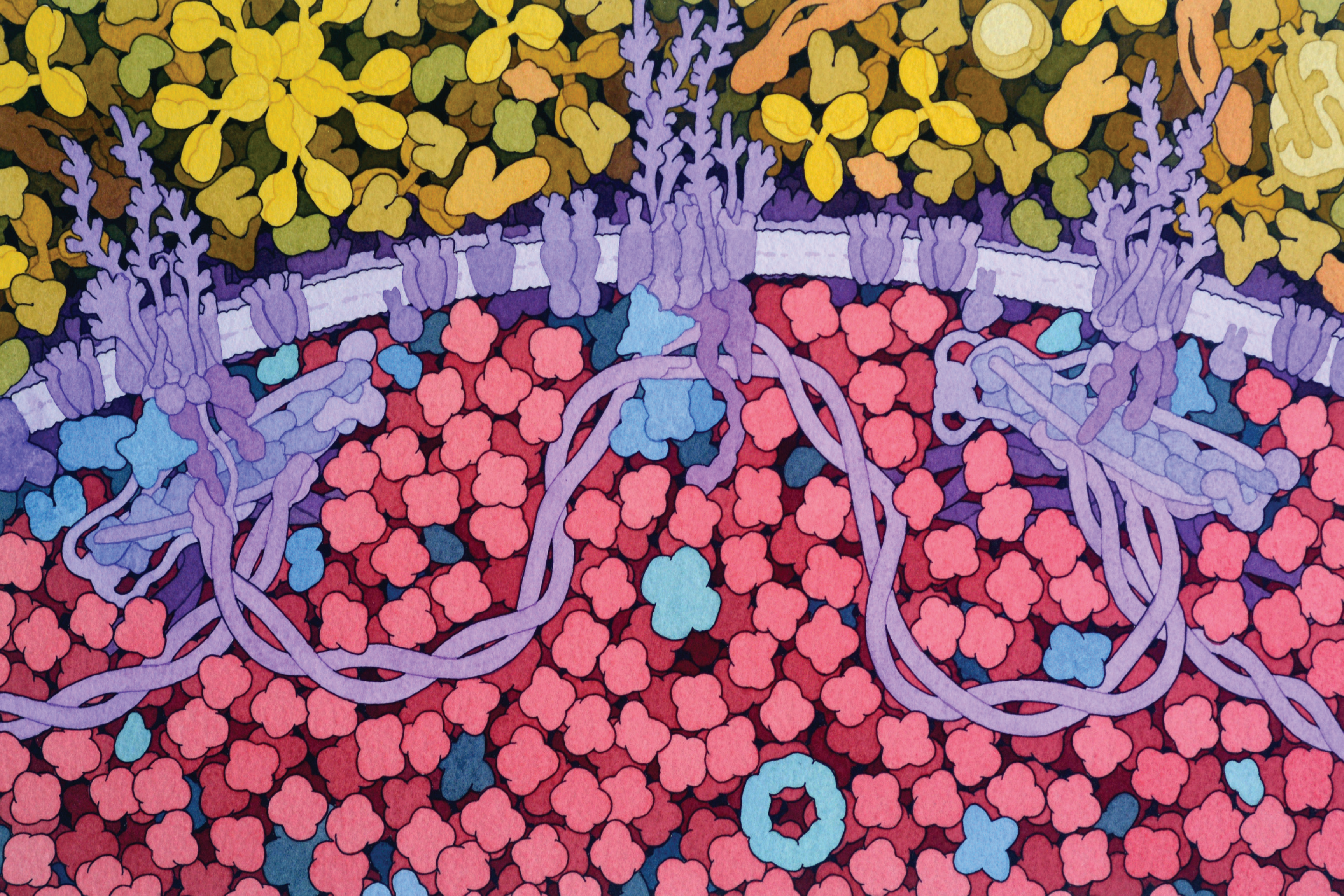
JANUARY 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
24	25 Christmas Day	26	27	28	29	30
31 New Year's Eve	1 New Year's Day	2	3	4	5	6
7	8	9	10	11	12	13
14	15 Martin Luther King Jr. Day	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31	1	2	3

Catalase

The molecular machinery of aerobic energy production occasionally produces reactive forms of oxygen. Our bodies contain highly efficient proteins for detoxifying these dangerous molecules. The active site of catalase is shown with a heme cofactor caught in the act of detoxifying hydrogen peroxide.

Learn more: **pdb101.rcsb.org**



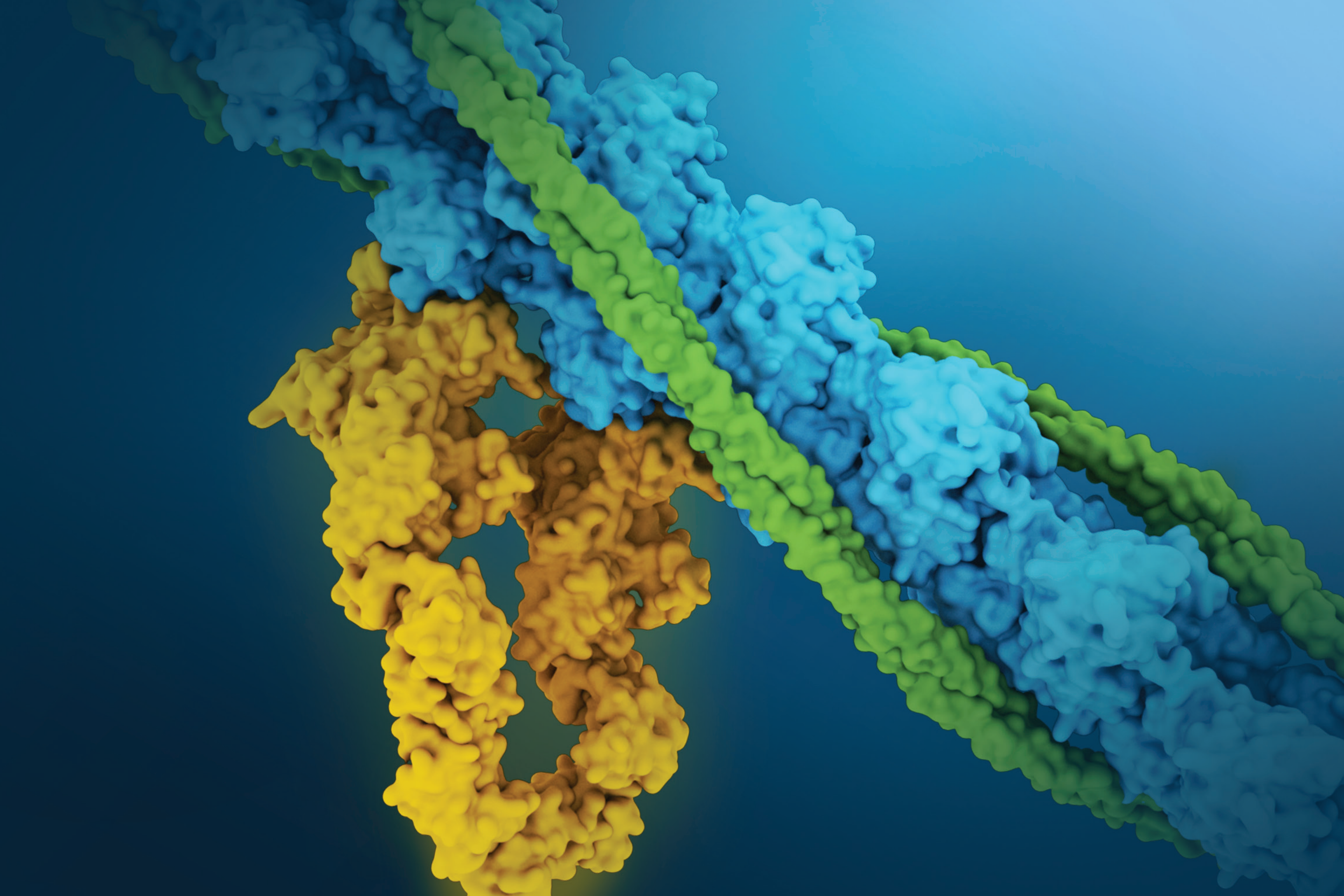
FEBRUARY 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
28	29	30	31	1	2	3
4	5	6	7	8	9	10 Lunar New Year
11	12	13	14 Valentine's Day	15	16	17
18	19 Presidents' Day	20	21	22	23	24
25	26	27	28	29	1	2
3	4	5	6	7	8	9

Hemoglobin

Our muscles, nerves, and brain require lots of oxygen, particularly during athletic activities. Oxygen is delivered to hungry cells by hemoglobin, the bright red protein in blood. Each hemoglobin molecule is made out of four protein chains with a heme cofactor, each of which can deliver a single molecule of oxygen. This function is so important that the action of hemoglobin has been tuned through evolution to use a remarkable change of shape to allow it to capture and release oxygen more efficiently than would be possible if it were composed of a single protein chain.

Learn more: **pdb101.rcsb.org**



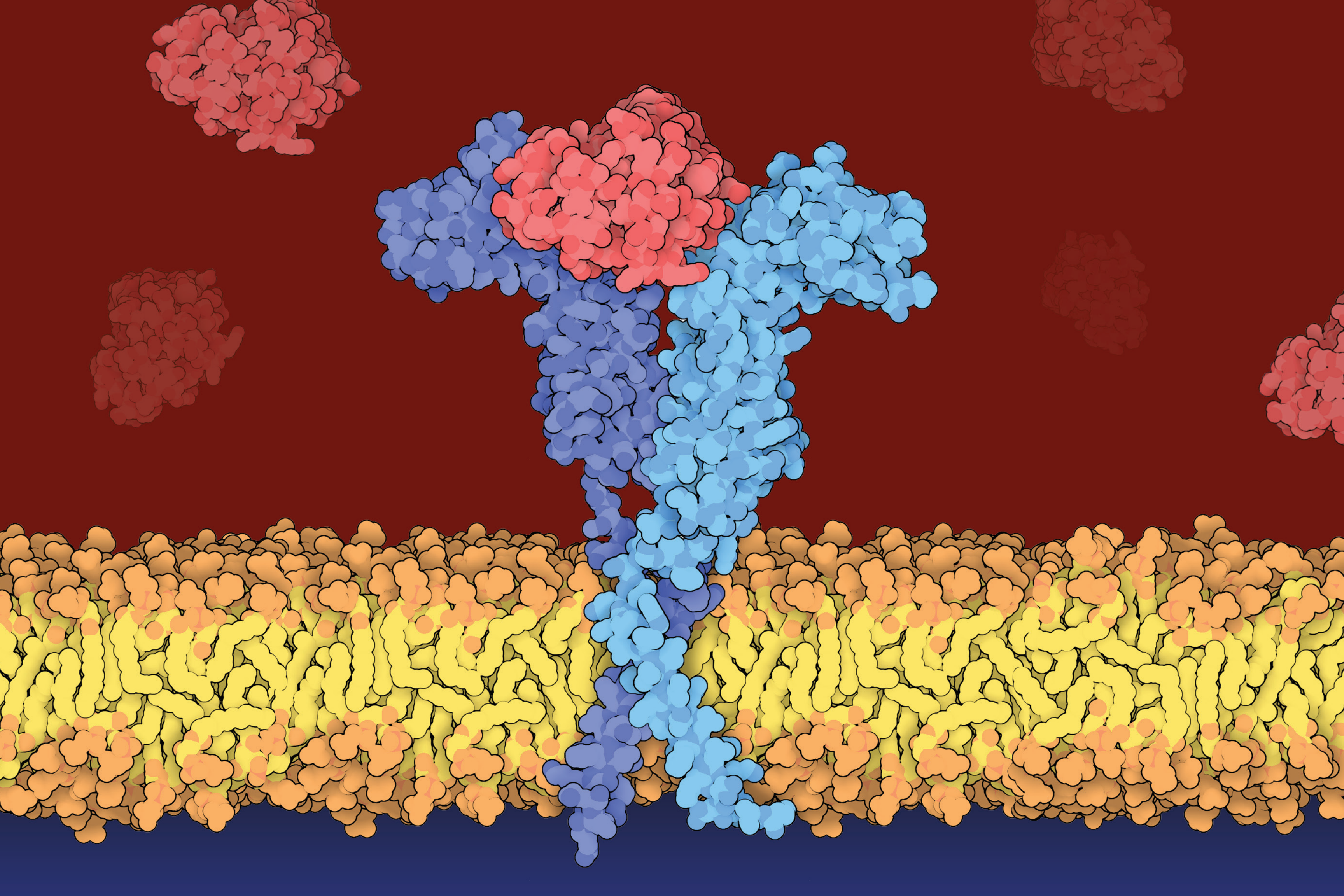
MARCH 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25	26	27	28	29	1	2
3	4	5	6	7	8	9
10	11	12	13	14 Pi Day	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31 Easter	1	2	3	4	5	6

Myosin

Muscles contract using an ATP-powered engine composed of actin (blue), myosin (orange), and many helper molecules like tropomyosin (green). Each myosin performs only a tiny molecular "power stroke", pulling itself along a long actin fibril. It takes about 2 trillion myosin molecules to provide the force to lift up a baseball. Our biceps have a million times this many, so only a fraction of the myosin molecules need to be exerting themselves at any given time. By working together, the tiny individual power strokes of each myosin are summed to provide macroscopic power in our familiar world.

Learn more: **pdb101.rcsb.org**



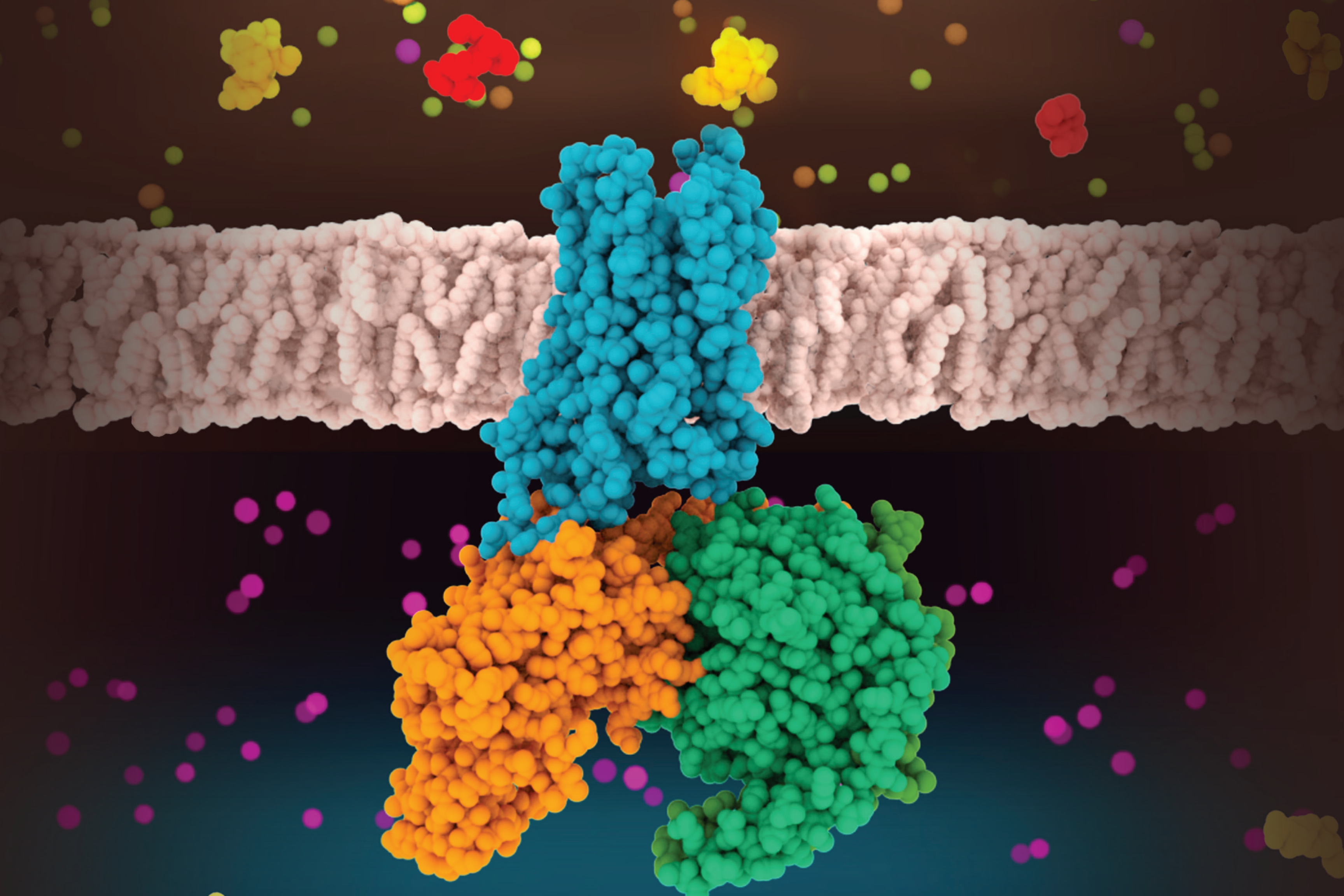
APRIL 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
31	1	2	3	4	5	6
7	8	9 Eid al-Fitr begins	10	11	12	13
14	15	16	17	18	19	20
21	22 Earth Day	23	24	25 DNA Day	26	27
28	29	30	1	2	3	4
5	6	7	8	9	10	11

Growth Hormone

Growth hormone (red) was identified in the 1920s as a growth-promoting protein secreted by the pituitary gland in the brain. By the mid to late 1980s scientists were able to produce this 191-residue protein hormone in bacteria using recombinant DNA technology. With the availability of large quantities of the recombinant hormone, therapeutic use became possible. Children and adults with growth hormone deficiency can now be treated with growth hormone supplements. Patients suffering from diseases that lead to muscle wasting and weakness (like AIDS) also benefit from such supplements.

Learn more: **pdb101.rcsb.org**



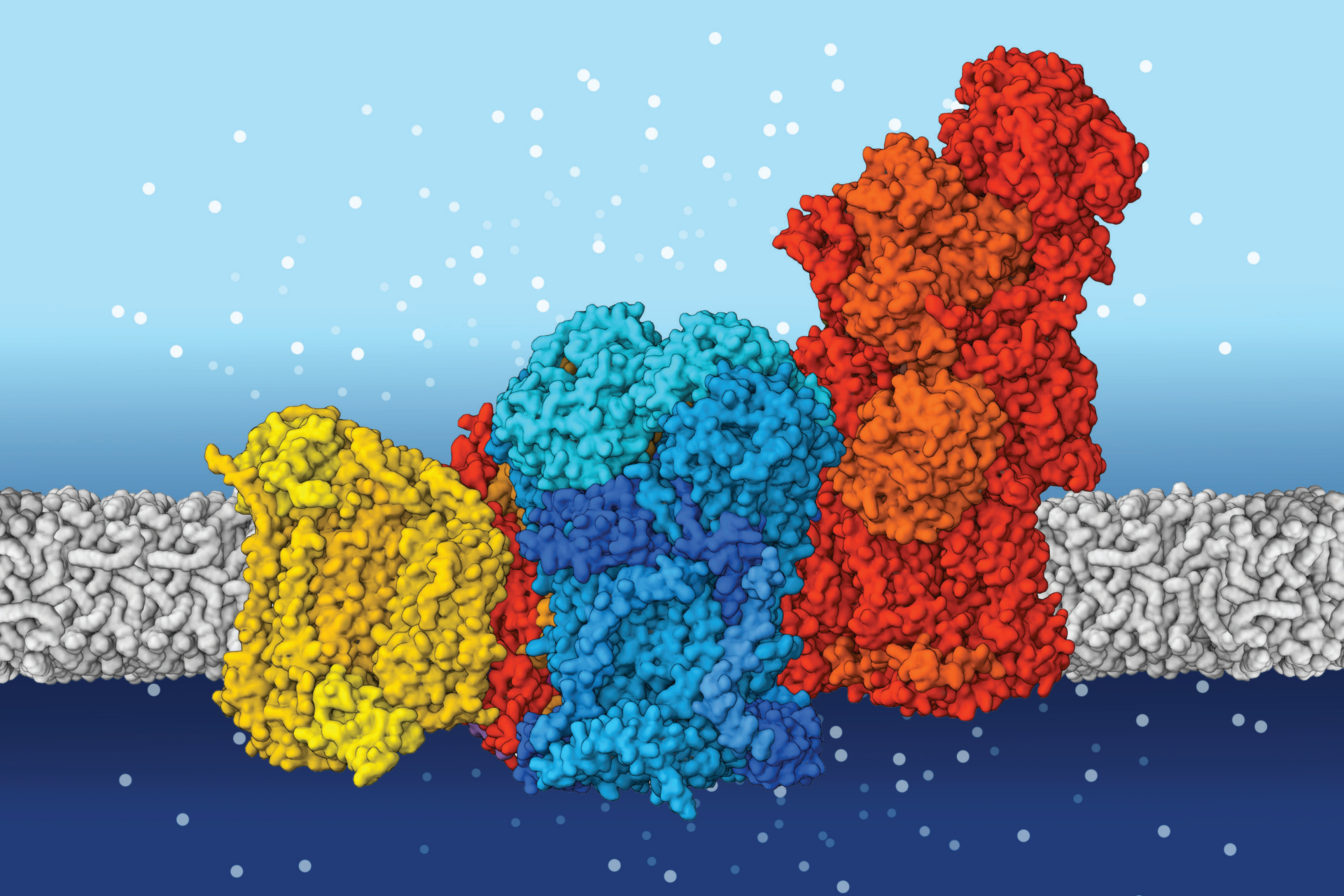
MAY 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
28	29	30	1	2	3	4
5	6	7	8	9	10	11
12 Mother's Day	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27 Memorial Day	28	29	30	31	1
2	3	4	5	6	7	8

Opioid Receptor

Our bodies make natural pain killers, including enkephalins (yellow), that suppress pain responses when needed, such as during heavy athletic activity. These pain killers bind to opioid receptors (blue), which are a type of G protein–coupled receptor (GPCR). Upon ligand binding, the two subunits of the G protein (orange and green) disconnect from the receptor and interact with other proteins, reducing the strength of the pain signal. As implied by the name, opioid molecules (red) bind to these receptors as well, providing a similar pain-blocking response.

Learn more: **pdb101.rcsb.org**



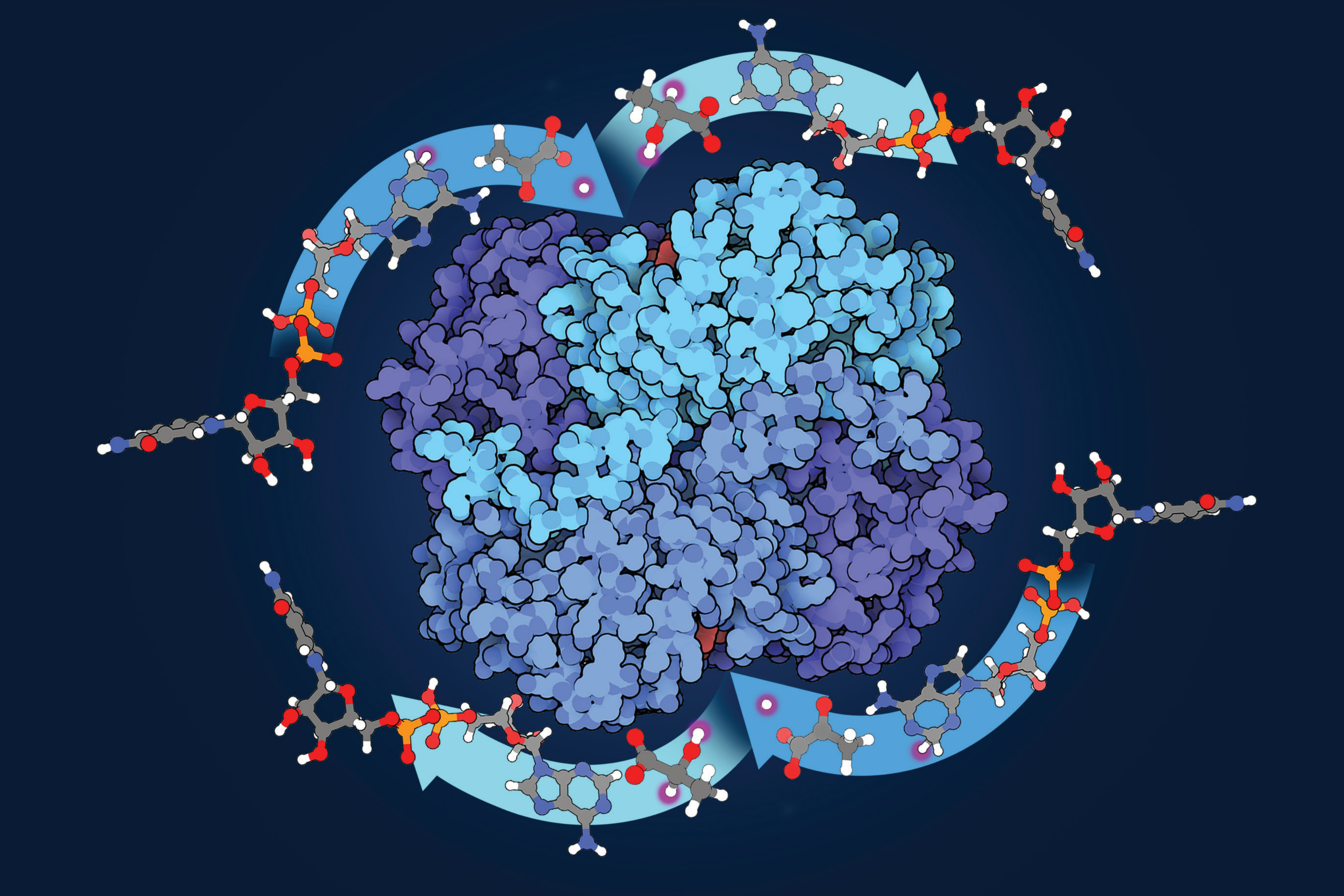
JUNE 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16 Father's Day	17	18	19 Juneteenth	20	21	22
23	24	25	26	27	28	29
30	1	2	3	4	5	6

Respiratory Supercomplex

Respiratory supercomplex performs the last step of aerobic energy generation in our mitochondria. It uses the hydrogen atoms from the breakdown of glucose. Electrons are stripped from the hydrogen atoms by Complex I (red), passed through Complex III (blue), and finally placed on oxygen in Complex IV (yellow). This movement of electrons is used to power creation of a gradient of hydrogen ions across the mitochondrial membrane, which is used like a charged battery to create the ATP needed to power muscles.

Learn more: **pdb101.rcsb.org**



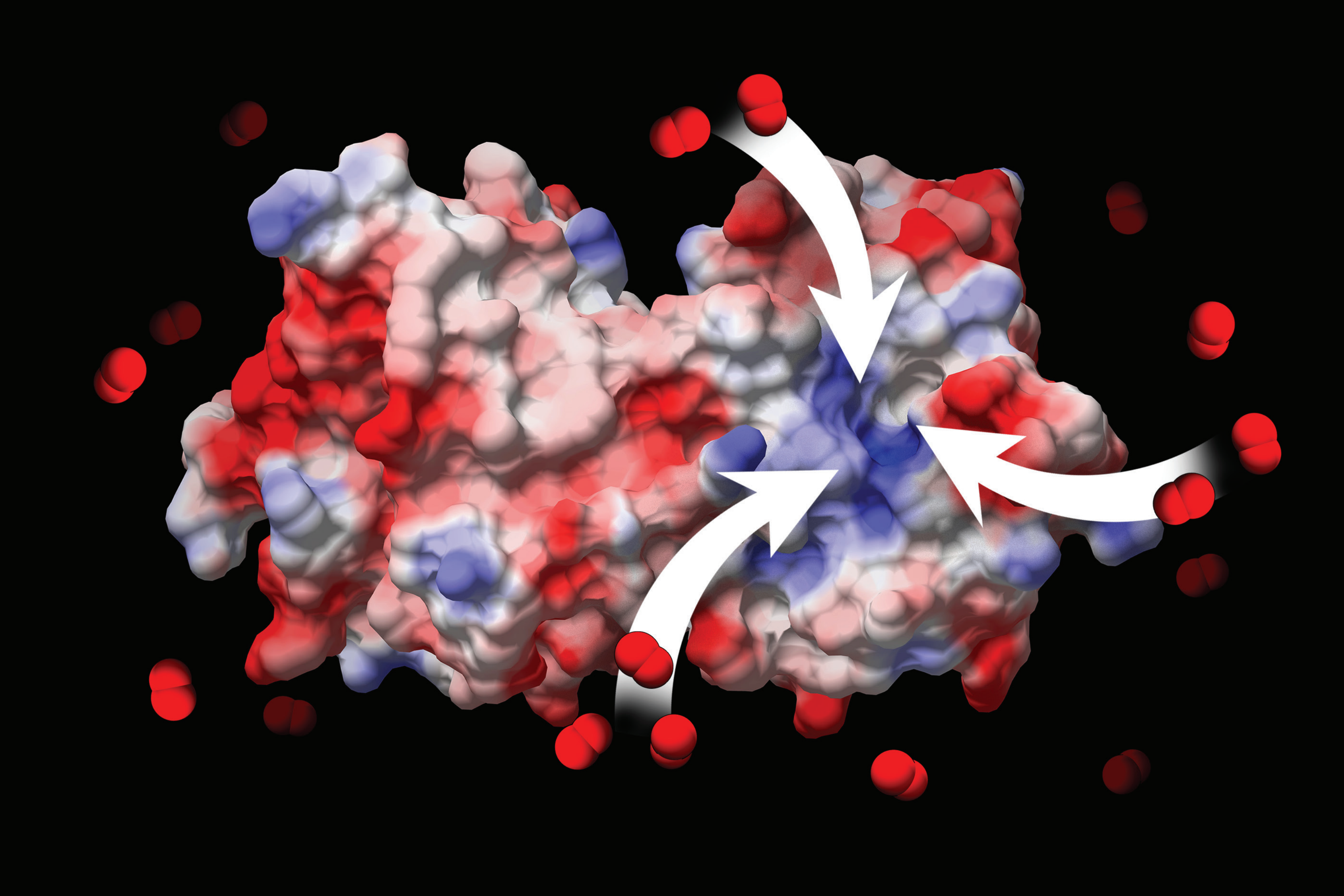
JULY 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
30	1	2	3	4 Independence Day (USA)	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31	1	2	3
4	5	6	7	8	9	10

Lactate Dehydrogenase

When we exercise at a normal (aerobic) pace, our cells get plenty of oxygen and sugar molecules are broken down quickly and efficiently. The final product of glycolysis, the pyruvate molecule, is the first substrate in the Citric Acid Cycle. However, when oxygen is in short supply during over-exertions like sprints, muscle cells turn to an anaerobic pathway of energy production. Lactate dehydrogenase converts pyruvate into lactate using NADH and a hydrogen atom left over from the breakdown of glucose. This process can produce the needed burst of energy for a sprint. However, lactic acid builds up and in a matter of a minute or so you have to stop and let your body recover. As you catch your breath, your body breaks down lactic acid using the normal process of aerobic energy production.

Learn more: **pdb101.rcsb.org**



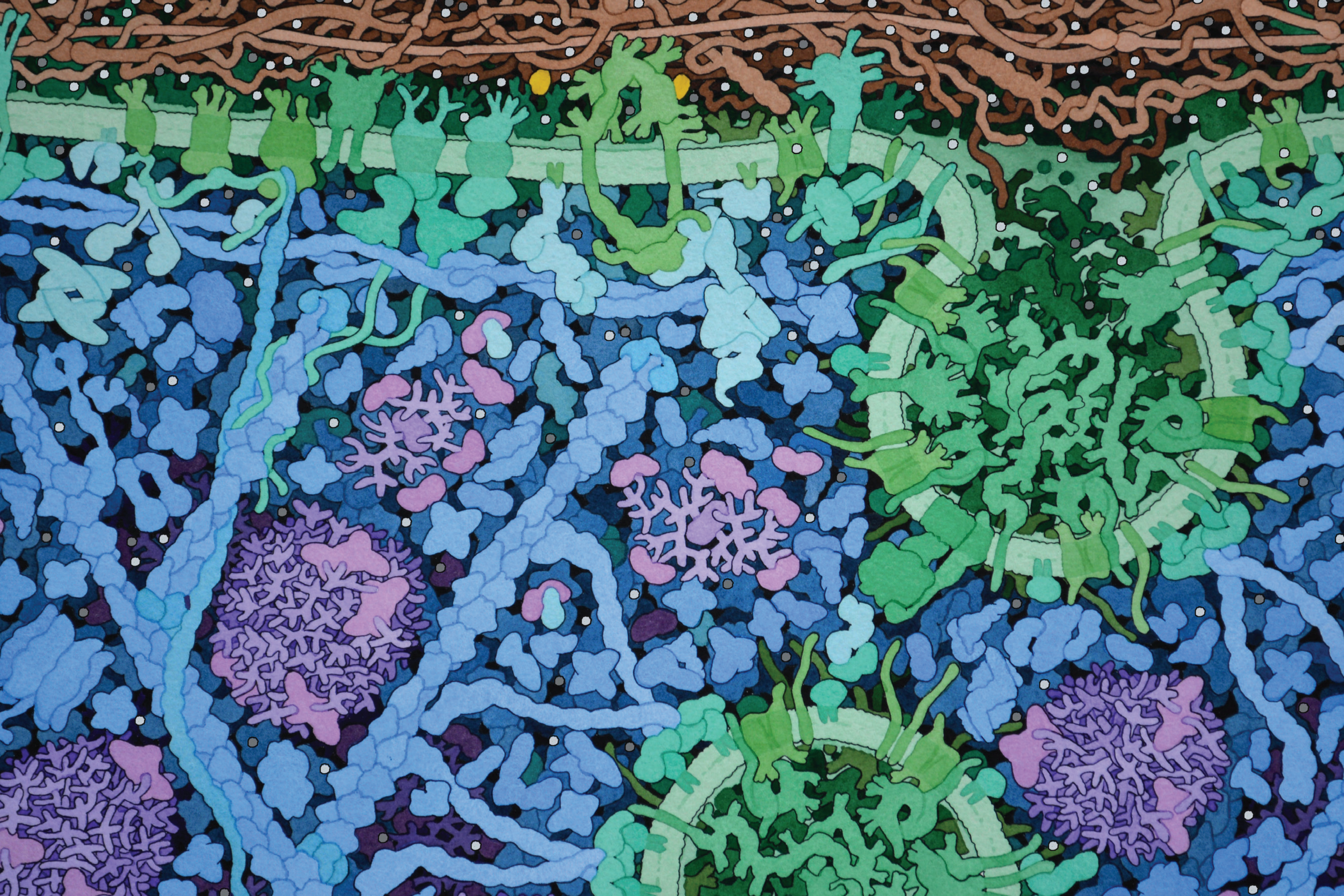
AUGUST 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
28	29	30	31	1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31
1	2	3	4	5	6	7

Superoxide Dismutase

Superoxide dismutase is an elite athlete in the world of enzymes. It helps detoxify reactive forms of oxygen, using copper and zinc atoms to assist with the chemical reaction. When researchers looked closely at the enzyme, they found that it performs the reaction faster than would be expected normally. The enzyme does this by steering reactive molecules into its active site using a positively-charged patch on the surface (the large blue patch to the right of center).

Learn more: **pdb101.rcsb.org**



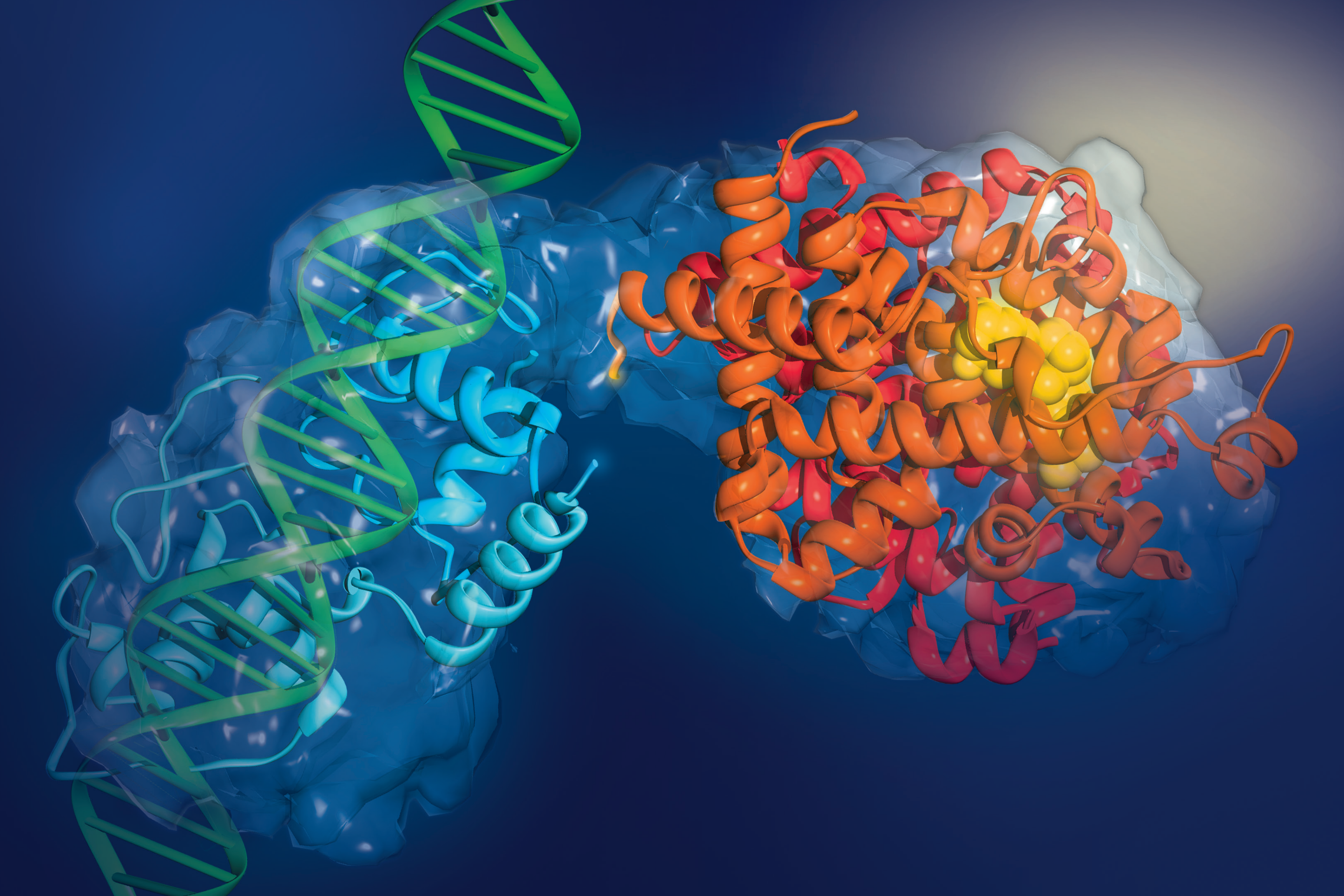
SEPTEMBER 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2 Labor Day	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	1	2	3	4	5
6	7	8	9	10	11	12

Glycogen

"Carb loading" is a nutritional strategy athletes use for building up additional stores of glycogen for later use during heavy exertion, like running a marathon. When we eat a lot of carbohydrates, the hormone insulin (small yellow molecule at top) directs cells to gather glucose from the blood and store it in the form of glycogen molecules (purple). Later, when glucose is needed, the enzyme glycogen phosphorylase releases glucose molecules for use in energy production.

Learn more: **pdb101.rcsb.org**



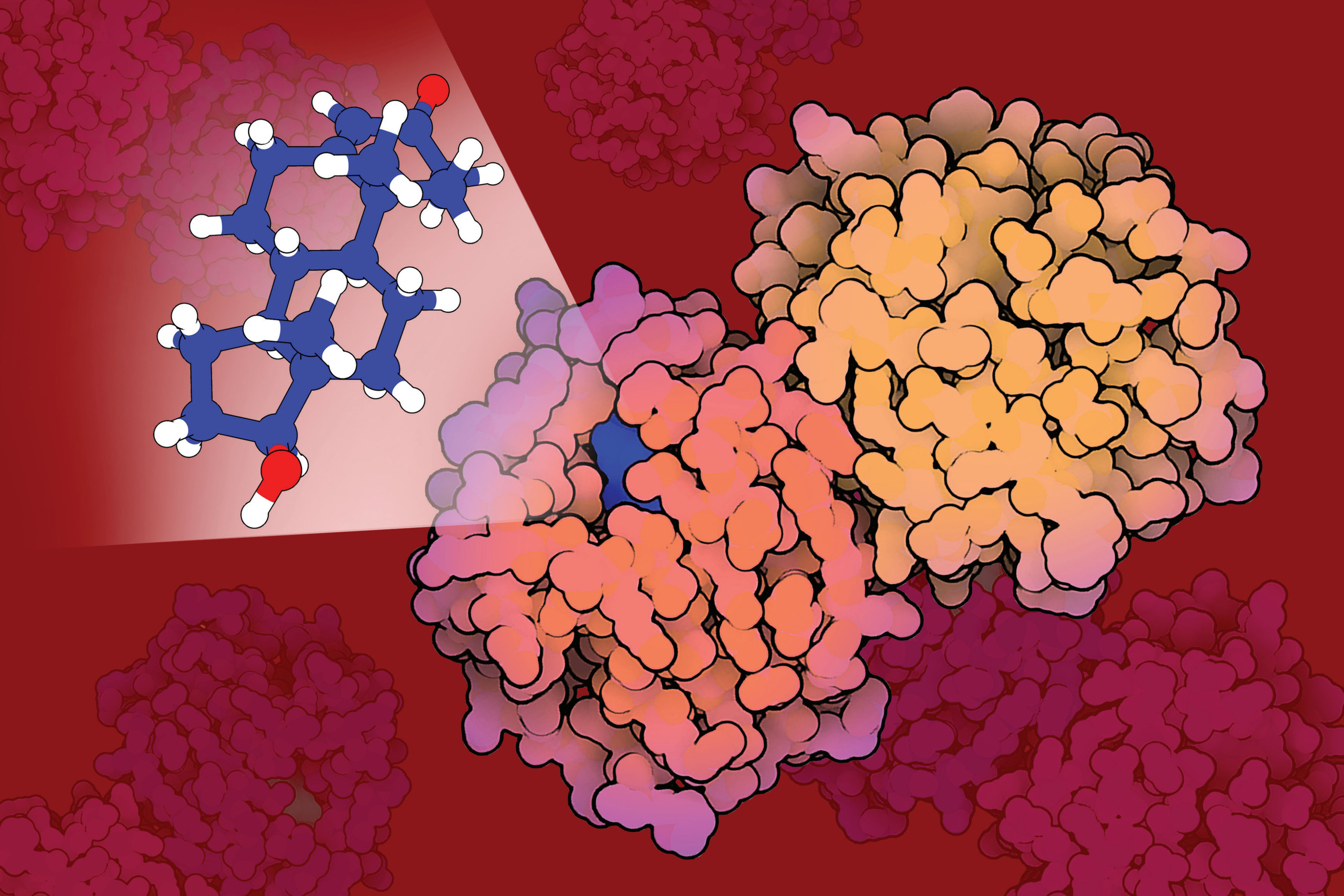
OCTOBER 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
29	30	1	2 Rosh Hashanah begins	3	4	5
6	7	8	9	10	11 Yom Kippur begins	12
13	14 Indigenous Peoples' Day	15	16	17	18	19
20 PDB announced in 1971	21	22	23	24	25	26
27	28	29	30	31 Halloween	1	2
3	4	5	6	7	8	9

Vitamin D Receptor

Vitamins are exotic molecules that are essential for the proper function of cells, but during the course of evolution, our bodies have lost the ability to make them. Vitamin D (yellow) is an exceptional case: our cells can make it, but only if there is enough sunlight. The ultraviolet rays in sunlight break down a form of cholesterol in our skin to make the vitamin. In polar or cloudy climates, however, people can go for months without sun, and the vitamin must instead be obtained in the diet (cod liver oil). In the body, vitamin D is converted into a hormone that binds to receptors (orange and red) that control synthesis of many different proteins involved in calcium transport and utilization. It plays an essential role in intestinal cells, where it helps control the uptake of calcium, and in bone cells, where it helps control formation and maintenance of the skeleton, making bones stronger when we lift weights.

Learn more: **pdb101.rcsb.org**



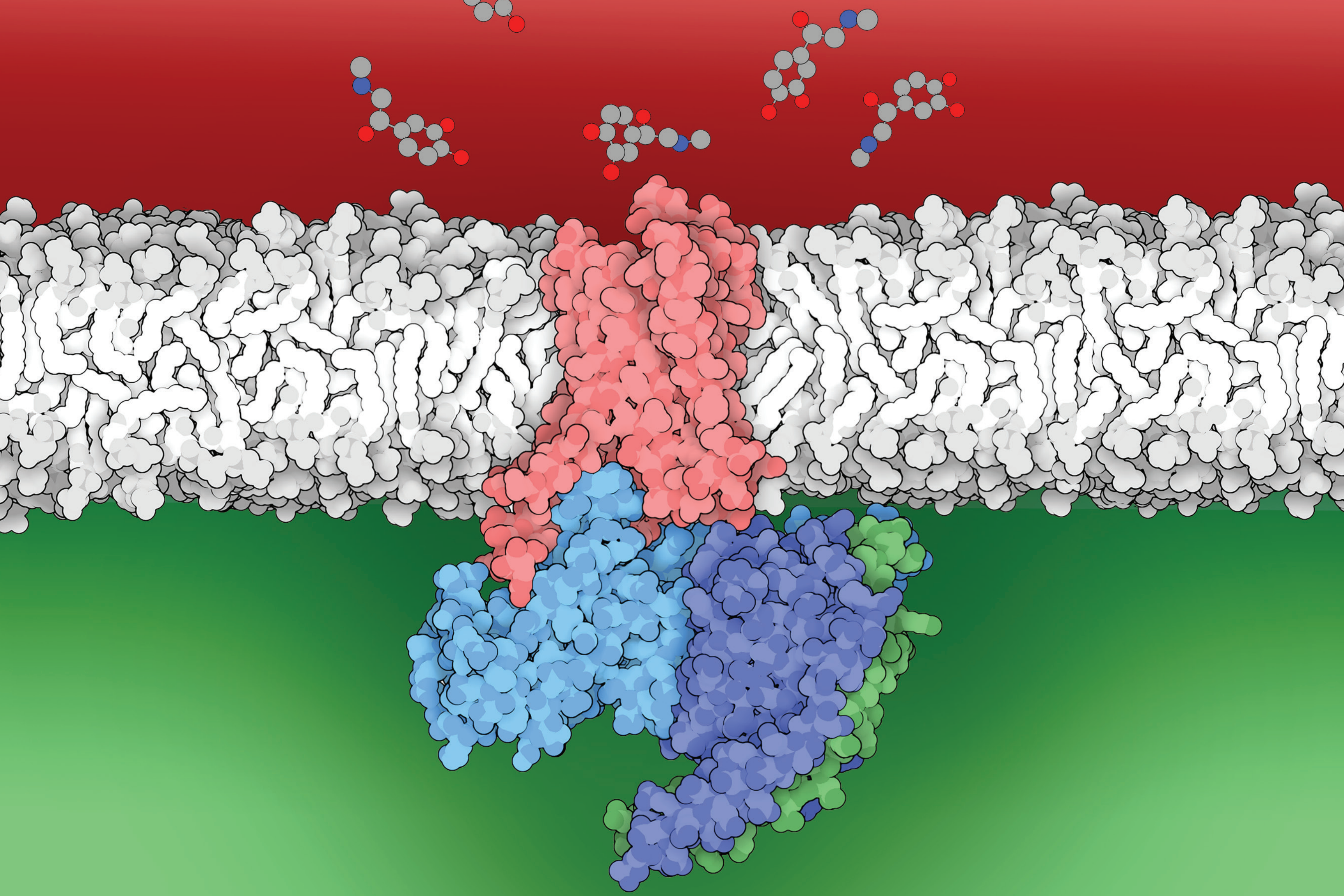
NOVEMBER 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
27	28	29	30	31	1	2
3	4	5	6	7	8	9
10 Diwali	11 Veterans Day	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28 Thanksgiving	29	30
1	2	3	4	5	6	7

Anabolic Steroids

Anabolic steroids like testosterone (blue) are among the most common performance-enhancing drugs. They have two major functions: controlling development and maintenance of “male” characteristics and regulating anabolic processes such as synthesis of proteins in muscle cells and formation of oxygen-carrying red blood cells. In the early 1960s, weightlifters and bodybuilders discovered that anabolic steroids improved performance in aerobic and endurance sports. Since then, these compounds have been used (and misused) by amateur and professional athletes. In 1975, the International Olympic Committee placed steroids on their list of banned substances, and most professional sports organizations currently ban their use. The sex hormone-binding globulin, shown here, transports testosterone in the blood from the testes to other tissues.

Learn more: **pdb101.rcsb.org**



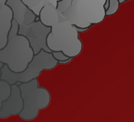
DECEMBER 2024

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25 Christmas Day	26 Kwanzaa	27	28
29	30	31 New Year's Eve	1	2	3	4
5	6	7	8	9	10	11

Beta-2 Adrenergic Receptor

When faced with danger, our bodies flood with adrenaline giving us a rush of energy. Defensive functions are activated, such as increasing heart rate and providing more sugar in the blood. Normal housekeeping functions, such as digestion, are temporarily halted as we respond to the challenge. This complex process requires different cells to respond differently to adrenaline–heart cells need to be activated, but cells in the digestive system need to wait for a better time to do their work. To orchestrate this range of responses, human cells build nine different types of adrenergic receptors, each with a slightly different effect. The one shown here, the beta-2 adrenergic receptor (red), stimulates cells to increase energy production and utilization. Other types of adrenergic receptors are inhibitory, reducing energy utilization. By expressing one type or another on their surfaces, different cells tailor their responses to adrenaline, making themselves ready for emergencies.

Learn more: **pdb101.rcsb.org**



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RCSB PDB is funded by the National Science Foundation (DBI-1832184), the US Department of Energy (DE-SC0019749), and the National Cancer Institute, National Institute of Allergy and Infectious Diseases, and National Institute of General Medical Sciences of the National Institutes of Health under grant R01GM133198.

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