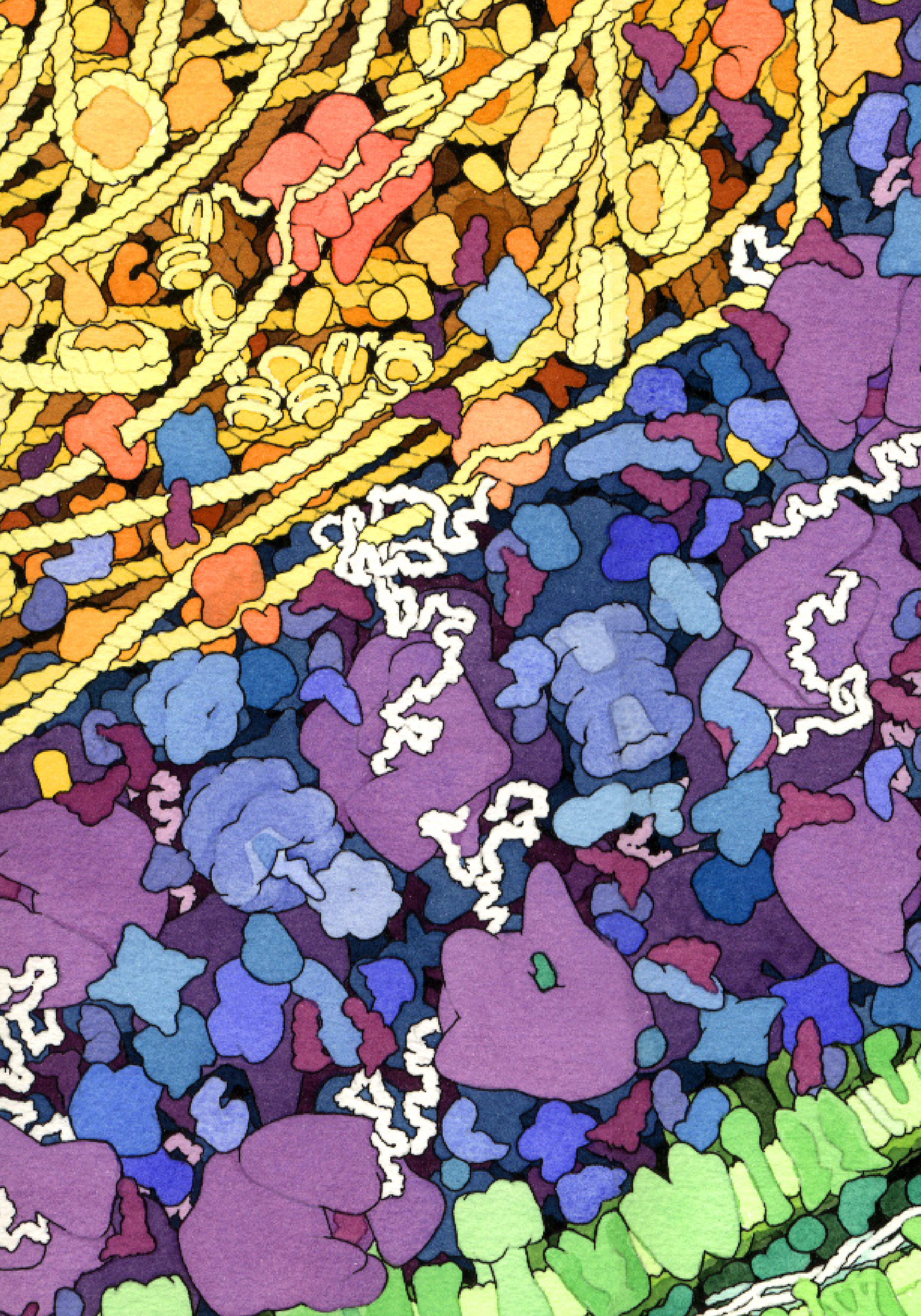
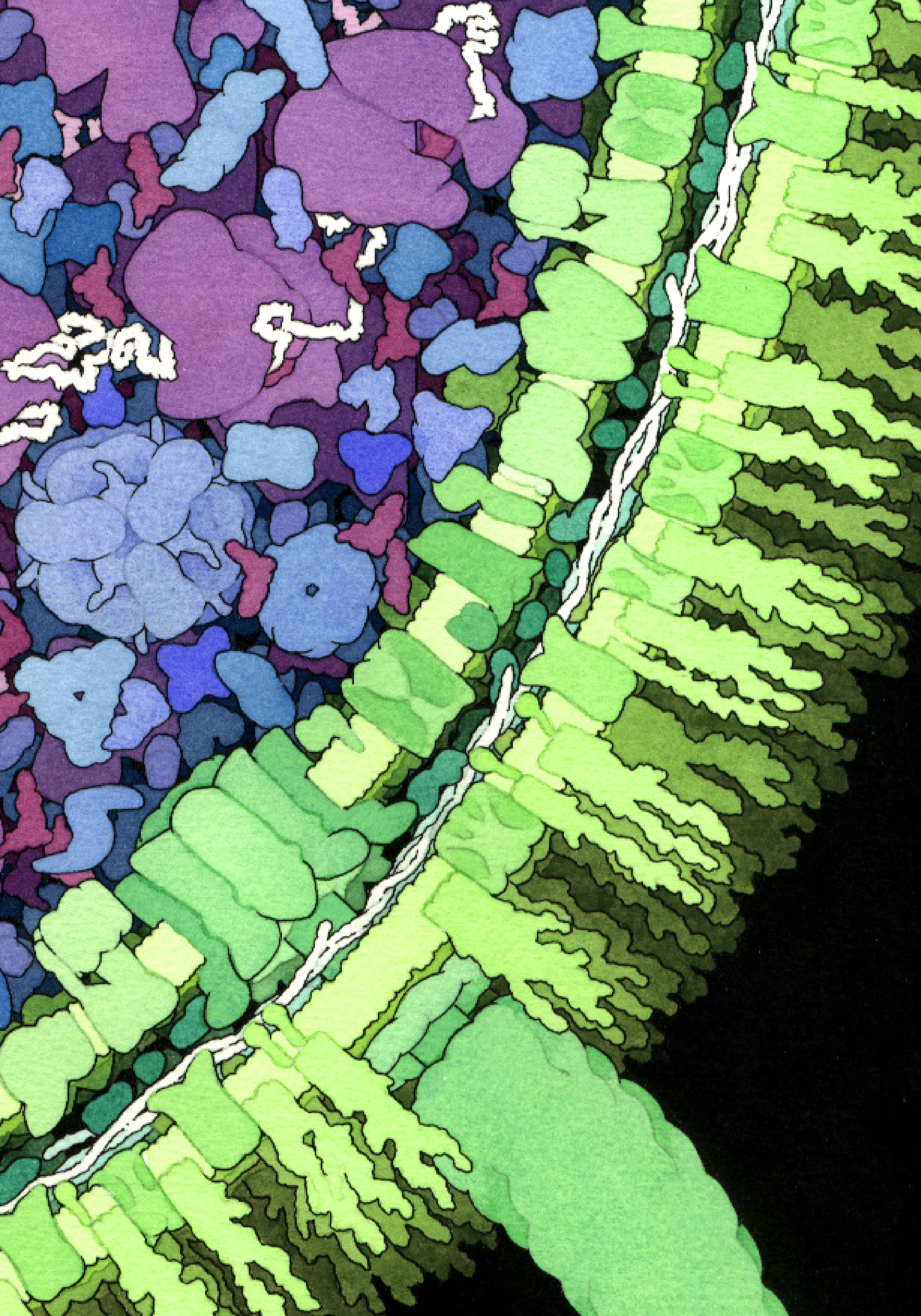
zq02

SUMMER 2012





About Zygote Quarterly

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Cover art

David Goodsell *Coated Pit*: This painting was developed in collaboration with researchers, educators, and students at the Center for Biomolecular Modeling at the Milwaukee School of Engineering. It shows the many proteins (in pinks and purples) that are used to pinch vesicles into the cell from the cell membrane (in green). The painting was used as part on an online "clickable" map for exploring the structure and function of the individual molecules: http://mgl.scripps.edu/people/goodsell/

pp 2-3: David Goodsell *Escherichia coli*: A cross-section through a bacterial cell is colored by the major structural features, with the cell wall in green, the cytoplasmic region with enzymes in blue and ribosomes in purple and the nucleoid with DNA in yellow and proteins in oranges.

Design

Marjan Eggermont

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Rainbow Shield Bug on Jatropha leaf: *Calidea dregii* (family: *Scutelleridae*, *Hemiptera*) on a leaf of Jatropha gossypiifolia. Pemba, Mozambique.

Photo: tonrulkens, 2012 | **Flickr cc**

Unlikely inspiration has sparked innovation in many fields, often coming in odd moments or in periods of rest after intense concentration. Bio-inspired design is replete with examples of this, possibly because of the wide mental reach necessary to link traditionally disparate subjects.

These stories mask an underlying bed of effort and lost ideas that is far greater than the “aha” moment, however. Although our better-known success stories seem to have sprung from the serendipitous, a natural selection process also seems to favor those new ideas that are covered in sweat. Tchaikovsky wrote: “inspiration is a guest who does not like to visit lazy people.”

Part of our mission at ZQ is to showcase the inventive spirit, and to learn how nature has inspired someone’s heart and mind. We also intend to provide an inkling of how an idea was transferred to the hands. How did she make it real? How did he make it stick? How can we do the same?

The subject of our feature article, engineer Eiji Nakatsu, formerly of JR West, is an embodiment of this blend of spirit and action. Curiosity, creativity, and hard work are evident in his legacy, an innovative train design sparked, first and foremost, by a love of nature. The train would not have run on its tracks, however, without the long labor for this love by so many, working together.

Thank you all for the effusive compliments and best wishes after the launch of our first issue. It has been most gratifying and has spurred us to strive harder to merit your continued support. Please let us know how we are doing at ZQ. ×

Tom McKeag, Norbert Hoeller, and Marjan Eggermont

Head Longlegged Fly (*Condylostylus*)

Photo: Thomas Shahan, 2009 | Flickr cc

In this issue

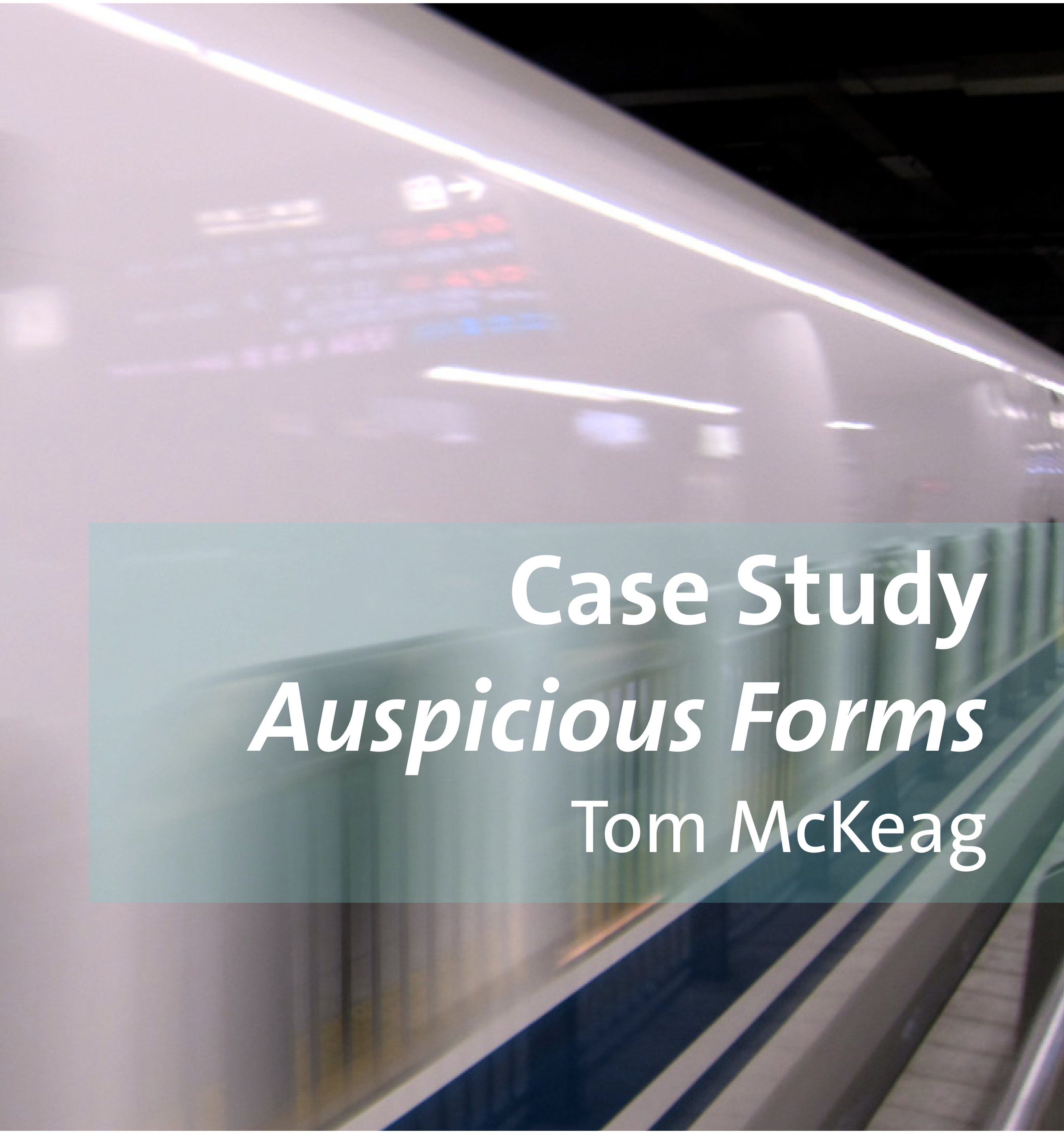
Welcome to our second issue of ZQ. Our lead article explains how Eiji Nakatsu, a bird watching engineer, improved the design of the Japanese Bullet Train by studying the owl and the kingfisher. We learn next about a designer in our ongoing interview of practicing professionals: Tom Knittel of the architectural firm HOK. Finally, we get two expert perspectives on R. Buckminster Fuller and his study of nature from Jay Baldwin and Curt McNamara.

We have added three new regular sections to our format: "portfolio", "opinion" and "tools". Our portfolio feature will present visually inspiring work of professionals in all disciplines. We are pleased to showcase the beautiful and informative images of scientist/artist David Goodsell. Our guest opinion page is intended to provide a platform for different opinions that will spark reasoned debate. This issue includes a provocative critique of popular biomimicry beliefs by Nikolay Bogatyrev. Our tools section introduces an engineering-to-biology thesaurus, a tool in progress by professor Jacquelyn Nagel.

We hope you enjoy this issue. ×

Shinkansen

Photo: wallyg, 2011 | Flickr cc



Case Study
Auspicious Forms
Tom McKeag

Auspicious Forms: Designing the Sanyo Shinkansen 500-Series Bullet Train

The Background

The tiny notice in his local newspaper in 1990 would prove to be auspicious, in the deepest sense of the word, but Eiji Nakatsu did not know this at the time. Even now he is struck by the fatefulness of the little printed square. Few details were given: a lecture about birds by an aviation engineer at the Osaka branch of the Wild Bird Society of Japan. He decided to go and hear what a fellow engineer would say about his favorite topic.

"Auspicious" is derived from the Latin root "Augur" and augury was the ancient Roman practice of studying the flight of birds in order to predict the future. It is a remarkably apt description of the next five years of Mr. Nakatsu's life; all set in motion by a scrap of newsprint. For Mr. Nakatsu was the General Manager of the Technical Development Department for one of the world's fastest trains, and he quickly realized that studying the flight of birds could indeed bring his train, and us, into the future.

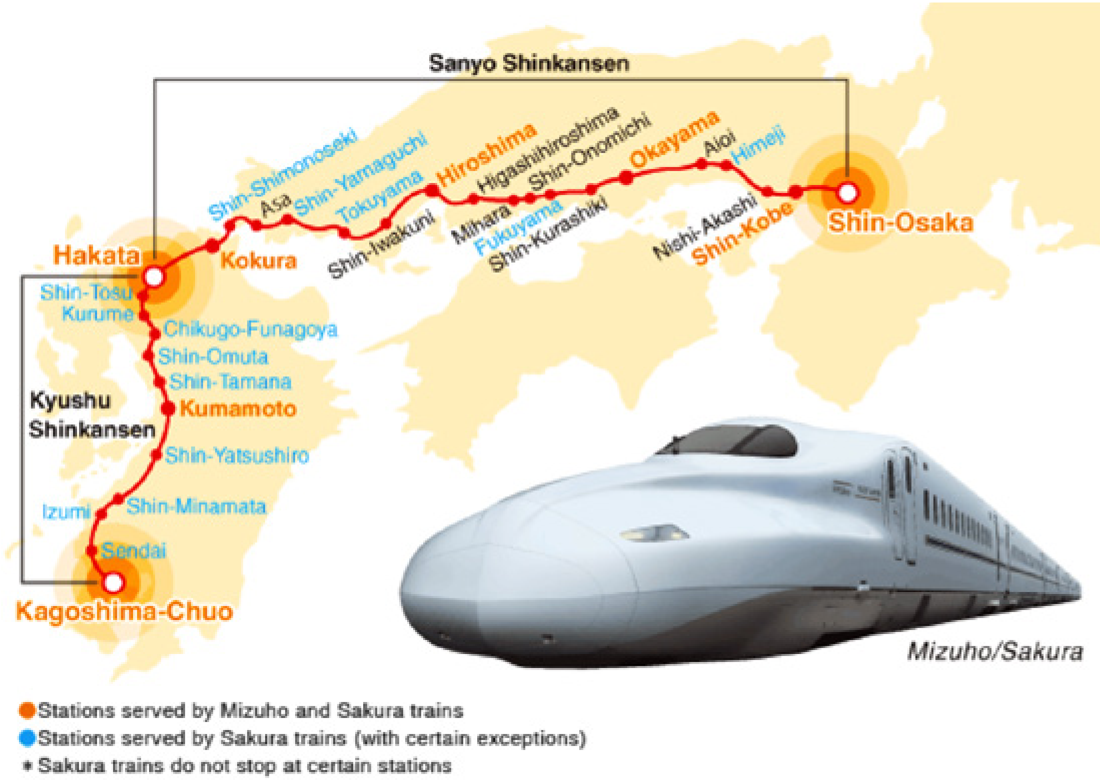
The Sanyo and Kyushu Shinkansen Lines, operated by Japan Railway West and Japan Railway Kyushu, run between Shin-Osaka and Kagoshima at the southern tip of Kyushu Island. The line connects western Japan's two biggest cities, Osaka and Fukuoka, and is an extension of the older Tokaido Line from Tokyo to Osaka.

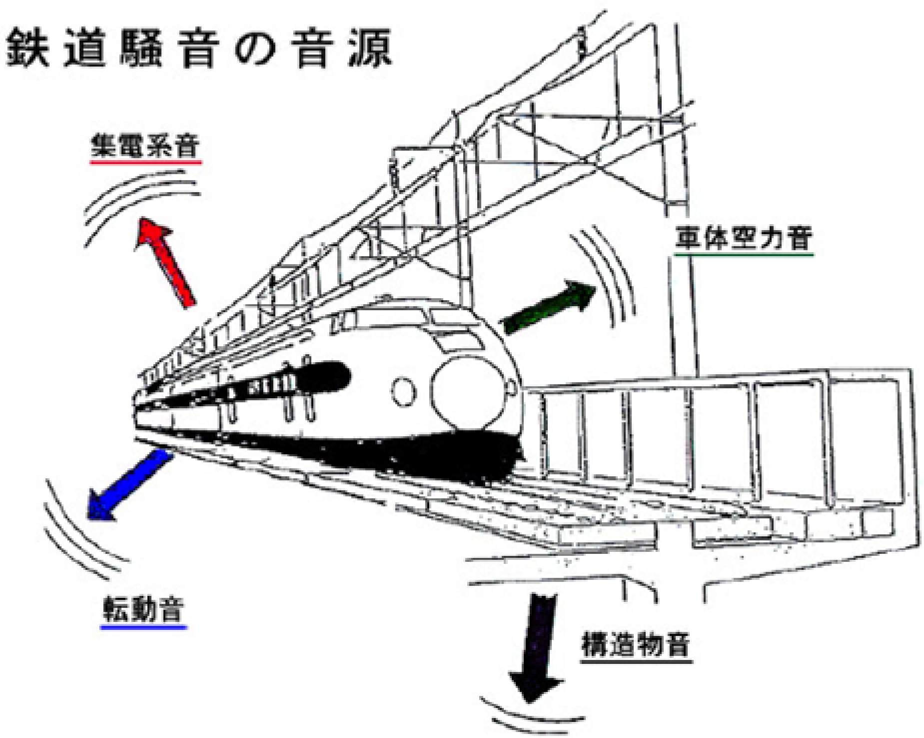
The 515 kilometer Tokaido Shinkansen is the world's busiest high-speed-rail line, having moved 4.9 billion passengers from its opening in 1964 (for the Toyko Olympiad) to 2010. Indeed, more people move by train in Japan than anywhere else in the world, and it is estimated that 64 million Japanese travel by rail of all sorts every day. Of this 40% share in world train traffic, 820,000 riders travel each day on the 2388 km of the total Shinkansen network.

Moving that many passengers per day demands speed, and on the western line train speeds rivaled the TGV of France at nearly 300km/hr. Making his train go faster, however, was not what was most on Mr. Nakatsu's mind when he attended the lecture. It was noise.

The Pantograph Problem

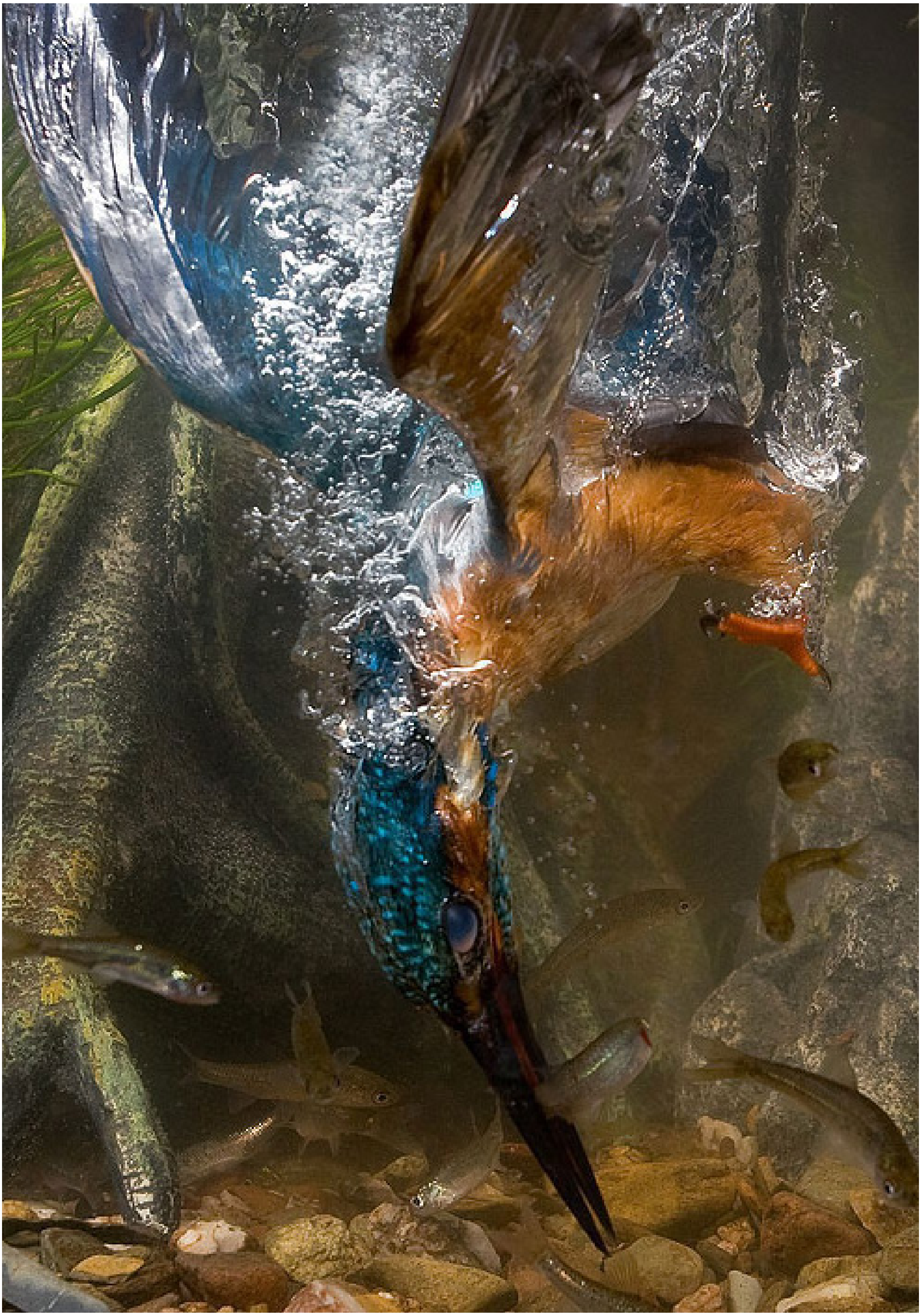
The noise standards for the Shinkansen Line, set in 1975 by the Japan Environment Agency, were some of the world's strictest for railway operation. This was because of the dense settlement patterns near the track, and two





Sanyo & Kyushu Shinkansen Route

Railway Noise Sources | Both images courtesy of Nakatsu, Eiji



Untitled (Kingfisher - deep dive) | Photo: edmerritt, 2011 | Flickr cc

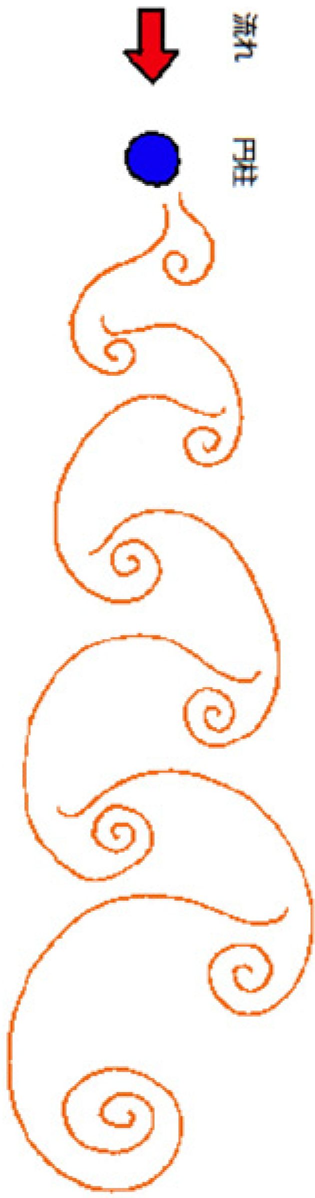
Eisvogel Alcedo | atthisedmerritt, 2011 | Flickr cc

zones were established, with 70 dB(A) and 75 dB(A) maximums allowed. The standards applied to the average peak noise of the ten loudest trains (among 20 continuous train runs), as measured 25 meters from the centerline of the tracks.

Mr. Nakatsu and his team had to solve this problem if they were to meet the five-year challenge set by the company leader: get a passenger from Shin-Osaka to Hakata station at Fukuoka in under 2 hours and 20 minutes. To do that the train would have to achieve speeds approaching 350 kilometers per hour. To develop this faster train they would have to build an entirely new test train or Electric Multiple Unit (EMU). Eventually the train would be named the WIN350 (for West Japan Railway's Innovation for the operation at 350 km/hr).

Technically, the WIN350 could reach the target speed, but the faster it went, the more noise it made. The noise was caused by three main factors. First, ground vibration was generated throughout the train and supporting structures to the ground when the train ran at the higher speeds. This rolling noise was generated at twice power of the velocity of the train. Second, aerodynamic noise was generated by the car body and the train's pantographs which connected the train to its overhead catenary wires. This aerodynamic noise became dominant at speeds above 200km/h and was 6th to 8th power of the train's velocity. Third, a sonic boom was being created whenever the train sped into a tunnel. On the 554 kilometer Sanyo Shinkansen Line (from Osaka to Hakata Station in Fukuoka), half the track was in tunnels. Reducing noise, therefore, became a critical criterion for an advancement in speed.

The physical phenomena of the three problems were quite different, and the last was, by far, the most complex. It is a testament to the problem-solving agility of the JR West team that the solutions to the pantograph noise and the sonic booms were inspired by the anatomies of two very different birds, the owl and the kingfisher.
In the case of the pantograph noise, air rushing over the struts and linkages in the mechanism was forming into so-called Karman vortices, also known as a Karman vortex street, and this turbulence was causing most of the noise. Karman vortices are created at all scales, from islands in the ocean to car aerials, and are manifested

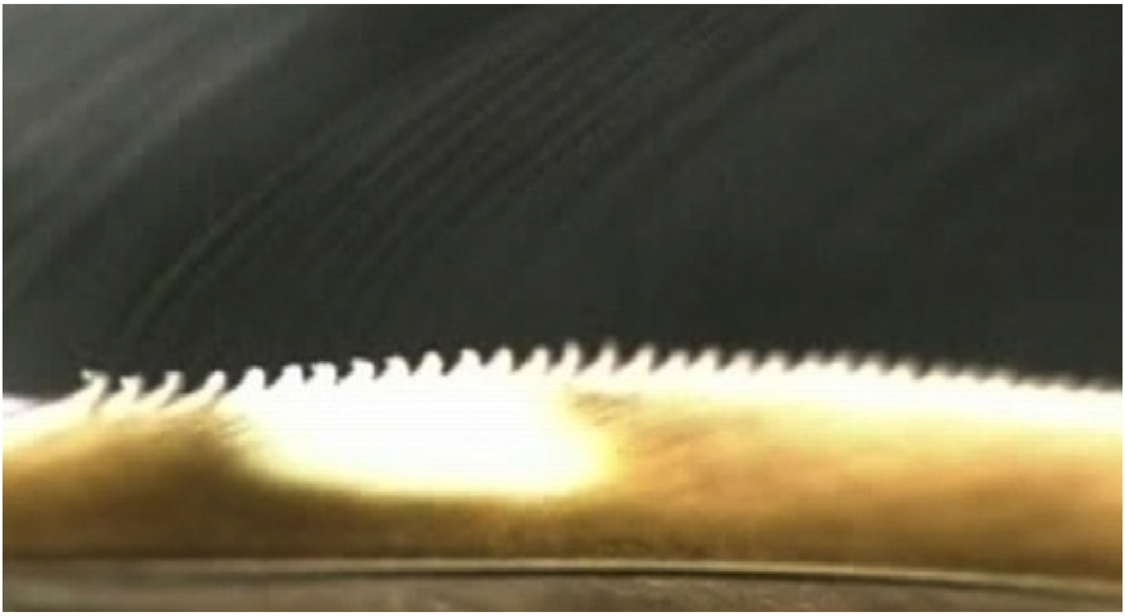


Causes of Aero Dynamic Noise (Karman Vortex) by Satomi Nakatsu

Image courtesy of Nakatsu, Eiji

Von Karman vortices off the coast of Rishiri Island in Japan

Photo: NASA, 2001 | Wikimedia Commons



Airflow with hawk and owl feather, 2008

Photo courtesy of Nakatsu, Eiji

Airflow with serrated owl feather, 2010

Photo courtesy of Nakatsu, Eiji

wherever a single bluff body separates the flow of a fluid. Alternate and opposite eddies swirl downstream of the obstruction, swinging back and forth as the force of one dominates and then the other. This turbulence is a major consideration in the design of any lone tower or vertical mast, and various ways have been devised to counteract it. Placing a leeward fin on a cylinder is an example. Vortex streets are a basic dynamic and indeed, some animals, such as bees, are thought to take advantage of it in their flight.

The JR West team had looked at several solution options and agreed on three basic paths: decreasing the number of pantographs, providing wind shielding covers for them, and designing an entirely new shape of pantograph that would help shed these vortices.

The team was able to cut the number of pantographs from eight to two or three, and designed molded windshields fore and aft of the remaining collectors. Quickly, the entire shield was integrated into one long pantograph cover. The cover, however, added weight to the train and affected the engineering of the tracks and energy use. Additionally, the cover itself was contributing to new vibrations and noticeable noise within the train. The cover was causing a new pressure wave when the train dashed into tunnels. The traditional engineering approach seemed to be causing problems as well as solving them, and the sorely tried team needed a fresh perspective.

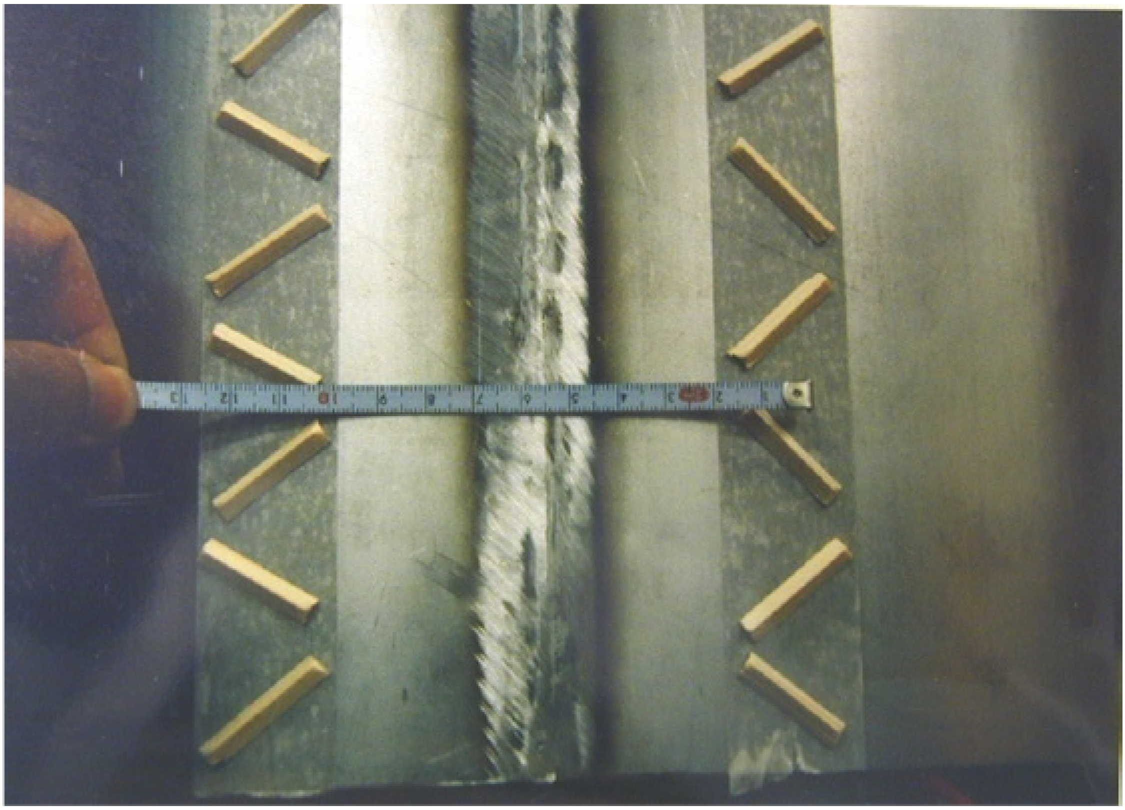
The Inspiration: the Owl

At the Wild Bird Society lecture Mr. Seichi Yajima, the aviation engineer, had taught Mr. Nakatsu much about how the physiology and anatomy of birds had influenced aircraft design. Mr. Nakatsu became intrigued with the owl's capability for silent flight. This nocturnal predator, in addition to having a precise locator system with its slightly offset ears, has several noise dampening forms in its feathers. Chief among them are the so-called fimbriae or flutings. These comprise a comb-like array of serrations grown on the leading edge of the primary wing feathers. The fimbriae serve to break down the air rushing over the wing foil into micro-turbulences and this muffles the sound that typically occurs in wings without this feature.

The Design Process

Could the serrated edge of a feather that enabled an owl to be such an efficient hunter be adapted to his noise problem? Mr. Nakatsu thought it could and set his team to test this tactic. They started with analyzing the owl wing itself, and borrowed a stuffed specimen of an owl and turtledove from the Tennoji Municipal Zoo at Osaka and placed them in a wind tunnel. They measured aerodynamic sounds from the two specimens and found that the owl's were clearly quieter. Next, they made a scale model of a wing shape and tested that for turbulence and lift in the tunnel. Finally, they made a full-sized prototype and tested that at the Railway Technical Research Institute (RTRI) test facility.

The refined pantograph prototype was, by now, markedly different from the mechanism it was to replace. The original pantograph design had not changed much in many years; a double-scissors arrangement that would have been familiar to anyone living at the turn-of-

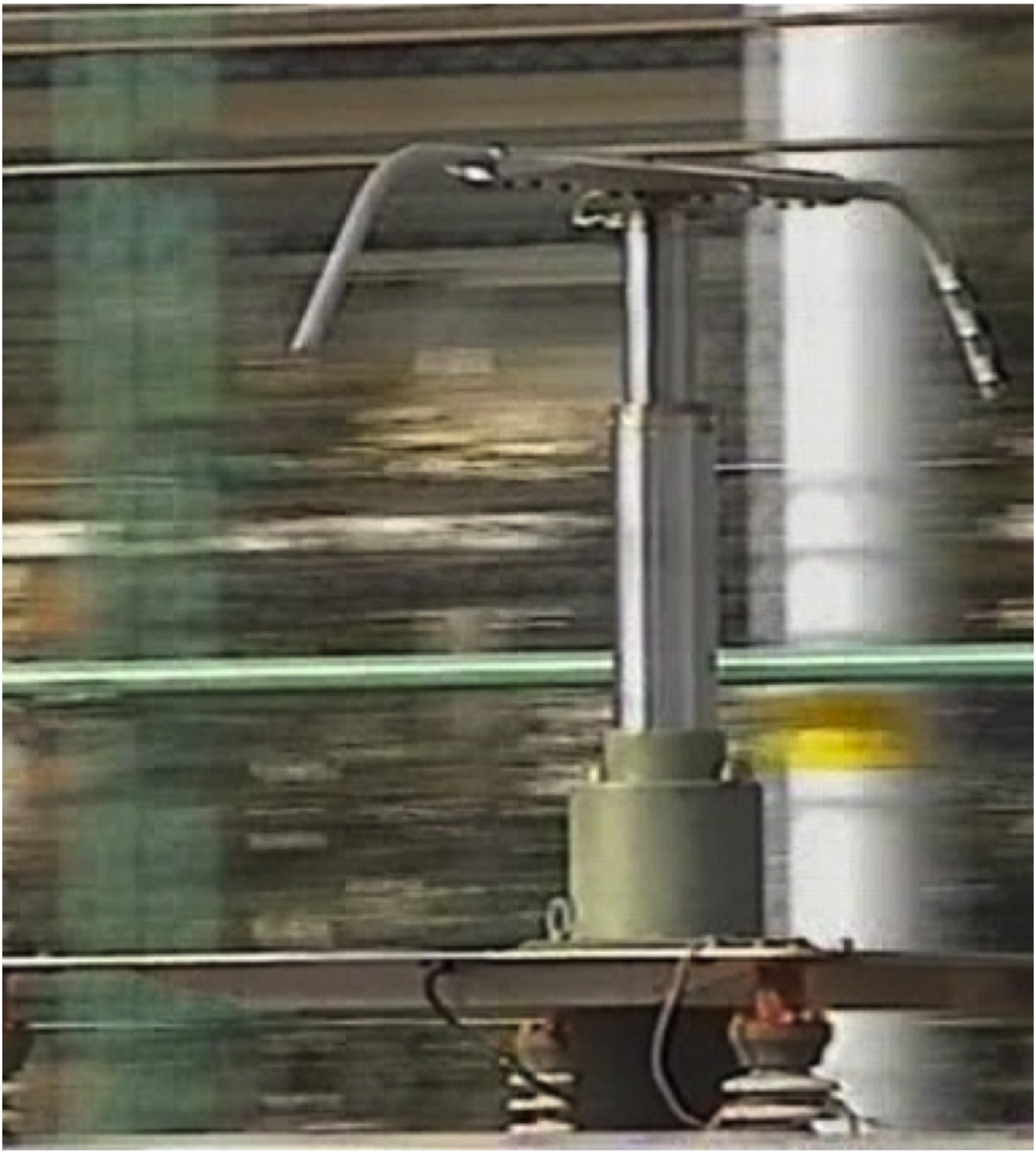


Serrations of the Owl's Feather (Mr.Yajima)

Triangle sectioned vortex generator at detached area

Photo courtesy of Nakatsu, Eiji

Photo courtesy of Nakatsu, Eiji



Wingraph power collecting test at RTRI
Photo courtesy of Nakatsu, Eiji

the-century. The new design comprised two streamlined parts: a pantograph slider (a flattened horizontal foil or wing of copper, iron and aluminum that served as a skid for the overhead live wires), and a aluminum vertical base or pillar, spindle-shaped in cross-section.

The team made a full-scale model and mounted it on top of a car at the Honda automotive test track. They studied the power collecting ability of the new design, first in the shop and then on the WIN350 test train on the main line.

Many important tests were made for airflow across the foil shape of the pantograph. JR-West had no wind tunnel of their own, so they received the critical cooperation of Sasakura Industry, Osaka University, Nissan Automobile, Mitsubishi Heavy Industry, Matsuda Automobile and RTRI for conducting these tests. The team's objective was to design a small vortex gene-rator (VG) as an integral part of the form of the pantograph, and thus reduce the air resistance and noise. The generation of small vortices prevents the formation of larger turbulence and subsequent drag and noise.

A similar VG application can be seen on the Boeing 737 jet aircraft, where tabs have been fixed, en echelon, along the top of the wing. Typically air flows over a surface, like a wing, in a laminar fashion, meaning that the particles within the fluid move parallel to each other in the same direction as the fluid as a whole, differing only in their speed. Inevitably, this efficient fluid flow must meet some change in condition and develop turbulence. Here, the particles within the fluid move in a highly irregular manner, and not in the same direction as the fluid as a whole. The purpose of the tabs is to preempt this change and make it manageable and more efficient: small whirlpools, instead of unruly big ones.

Unlike the aircraft wing, the Shinkansen pantograph base was vertical in orientation and blunter in cross section. What the JR West team discovered in the airflow test was a vertical line of turbulence at the top of the curve of base cylinder, where the smooth laminar flow, induced by the leading edge, began to break up. It was here that they would place their vortex generator (VG), a man-made fimbriae form inspired by the owl and its feathers.

While they now knew where to place the comb structures, they did not know how these small vortex generators should be shaped or arrayed, and went back to testing alternates for airflow performance: different cross-sections (convex, hemispherical, triangular, boxed, concave) and different orientations (horizontal, vertical, staggered). They even tried dimpling the surface like a golf ball, and found that this increased noise. They chose a triangular cross-section, arrayed

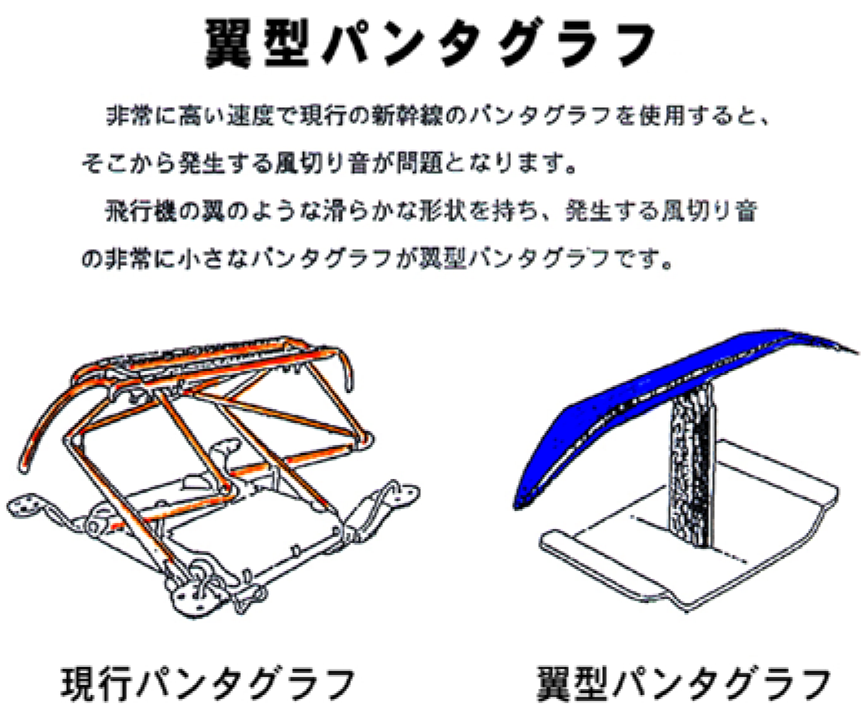
Testing the Concept: Then and Now

The JR West team faced two basic problems that required testing: noise caused by vortex shedding at the pantographs (overhead power line connectors) and sonic booms caused by air pressure waves pushed out of tunnels when trains passed through them.

Both of these challenges required years of extensive physical testing of conditions and prototypes. The team tried and recorded phenomena in a wide range of scales, from scale-model to full-size prototype, to a custom test train. Much of this research was conducted without the benefit of the kind of digital simulation programs available today. Hence, stuffed owls were placed in wind tunnels, solid shapes were dropped into water, projectiles were shot through pipes, and mockups were strapped to car tops in order to approximate conditions on the train. The ingenuity of the team was remarkable!

While there is no substitute for physical testing, simulation modeling can speed the test process, lower costs and increase the design options. We spoke with Luke Mihelcic, Product Marketing Manager with the Simulation Technology team at Autodesk, and he explained how some of their products might be used for similar challenges.

After the initial inspiration from the owl or kingfisher, an artifact from each organism could be scanned and drawn in a CAD file, or even photographed and imported directly into a program to be drawn over. This file could then be used in a simulation program. While there is no master database of aerodynamic shapes from nature,



Wingraph and Members of the Aero Dynamic Committee | Wingshaped Pantograph=Wingraph | Courtesy of Nakatsu, Eiji in two vertical lines of "v-shaped" pairs on opposite sides of the line of most turbulence. It had been the late Mr. Yajima, the aeronautical engineer and bird watcher, who had eventually proposed the array.

The Solution

Having satisfied themselves in the shop that the airflow around the pillar had been made smoother, the team set up the new "wing-graph" on the WIN350 EMU test train on the main line for the final field tests in March, 1994. Microphone arrays were set at intervals along the line and the train was run at the faster speeds.

It was a great success. The train could now run at 320 km/hr at 73 dB(A) and meet the 75 dB(A) noise standard. The improvements had added benefits in a slightly higher fuel efficiency and increased rider comfort within the train. When train noise fell below the 75 dB(A) level, public complaints were reduced dramatically.

The JR West team had solved the aerodynamic noise problem of the pantograph by using a combination of standard engineering approaches and bio-inspired innovation. They had started with reducing the source of the noise by limiting the pantographs to two for every 400 meters of train. They had applied traditional design techniques in shaping new pantograph covers to reduce turbulence to a manageable level. Finally, they had incorporated a mechanism found in nature into a redesigned form in order to eliminate the remaining noise. To apply this lesson to their problem they had meticulously observed a natural phenomenon (vortex generation) as it was employed by an organism (the owl in its feathers), and had translated its principles to the requirements of their challenge. During the problem-driven design process they had then doggedly tested prototypes through a wide range of salient conditions.

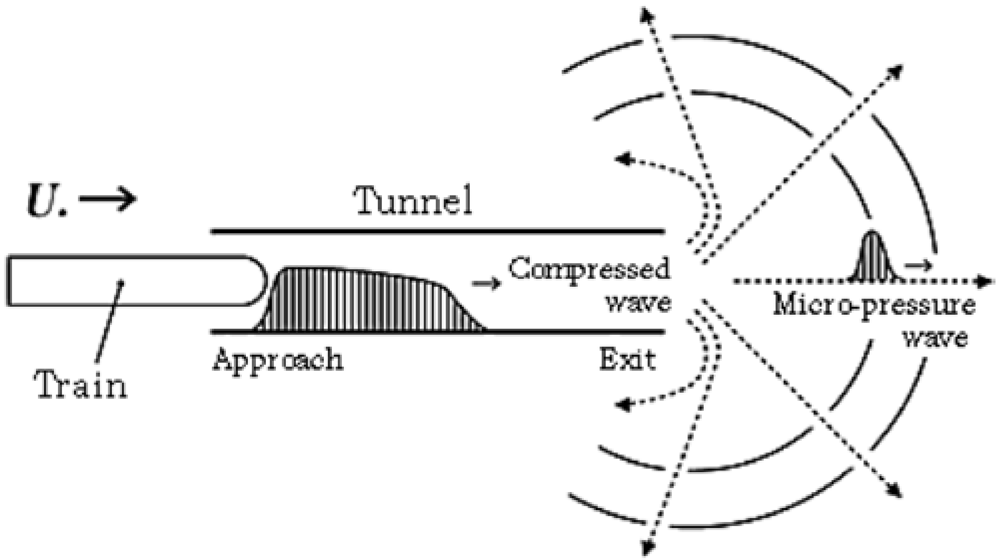
The Tunnel Problem

The sonic boom problem was much more complex than the pantograph noise. Whenever a train sped into a tunnel it generated atmospheric pressure waves that reached the tunnel exit at the speed of sound. Like a piston in a cylinder, the train was forcing the

an engineer might, typically, call up an assortment of aerodynamic shapes after a Google search and supplement with natural shapes gleaned from his own research.

At an early conceptual stage, even a roughly drawn shape could be placed in Autodesk's Project Falcon, a conceptual phase tool that measures external airflow exclusively using Autodesk Alias models or other 3D files. Falcon has the capability of providing real-time feedback to the designer about resultant forces like lift and drag. It is also interactive, allowing the designer to change parameters like speed and attack angle.

Once a promising basic geometry has been established, the digital prototypes would then be run through a Computational Fluid Dynamics (CFD) program like Autodesk Simulation CFD. The program is a comprehensive fluid flow analysis tool and is compatible with a wide range of other programs like Autodesk Inventor, SolidWorks, Pro/Engineer, UG, and NX. In this program an issue like vortex shedding could be simulated for hundreds of conditions and compare the variations to judge best fit, and the program tool Autodesk Inventor Fusion would enable the designer to edit and create new designs. The performance of each variation could also be quantified, recording

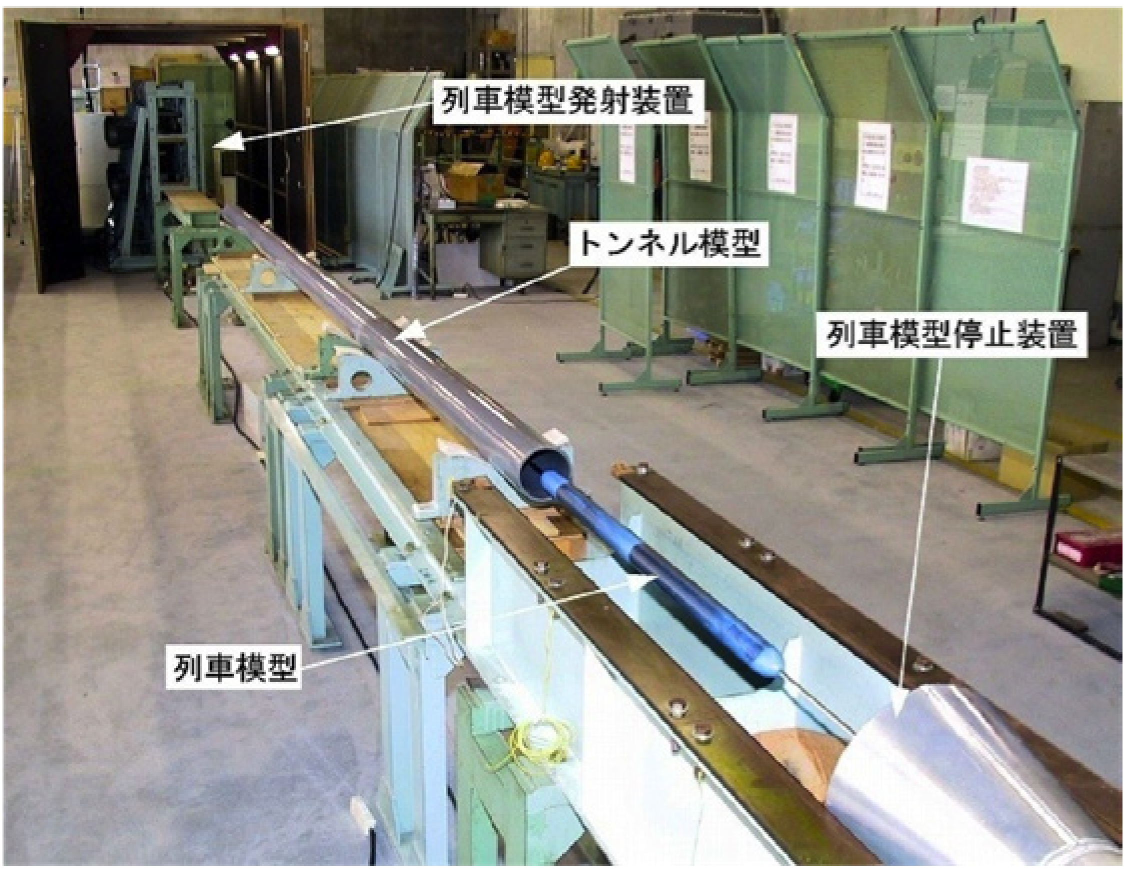


Tunnel Micro Pressure Wave Generating Mechanism

Image courtesy of Nakatsu, Eiji

Ruddy Kingfisher (*Halcyon coromanda*) | Ueno Zoo, Tokyo, Japan

Photo: Wikimedia Commons



Testing bullets

Photo courtesy of Nakatsu, Eiji

Experimental device for train model ‘shooting’

Photo courtesy of Nakatsu, Eiji

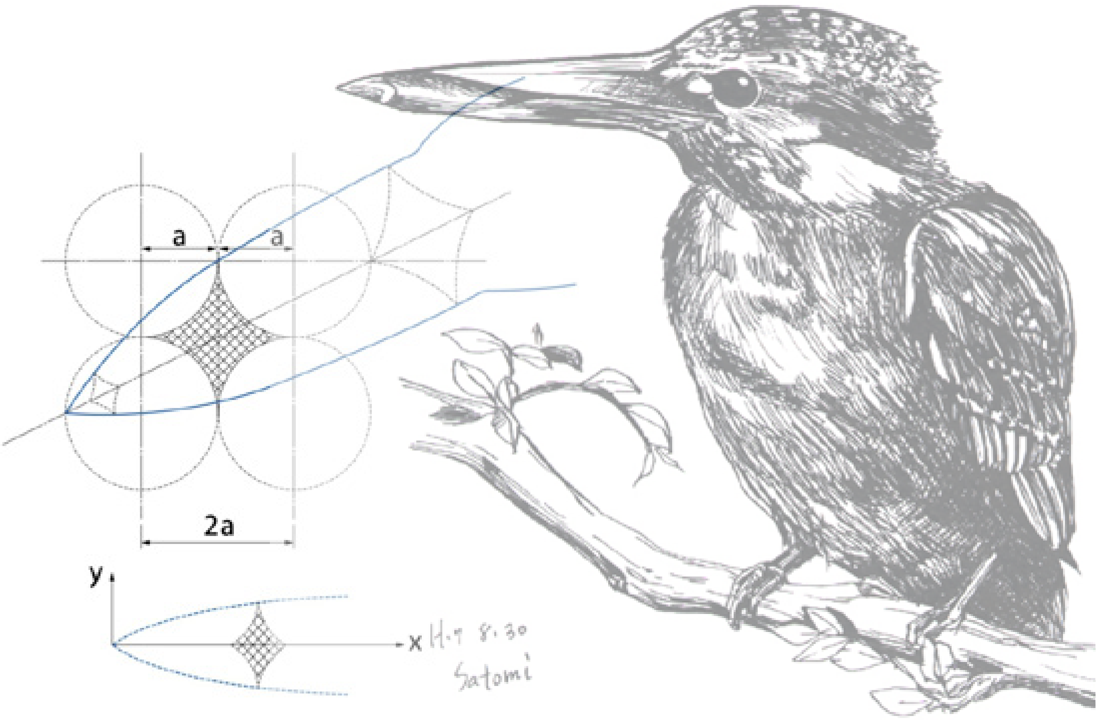


図7　カワセミ（翡翠）　クチバシと頭部形状

The bill of the Kingfisher: a revolving paraboloid shape with a sectional area that changed by a constant rate.
Image courtesy of Nakatsu, Eiji

Skeleton Specimen of Kingfisher's Head(by Mr.Ueda Mitsuhiro)
Photo courtesy of Nakatsu, Eiji

Kingfisher (Nakatsu,Satomi)
Image courtesy of Nakatsu,Eiji

fluid air out of the other end of the tunnel. Because the pressure emitted at the tunnel exit was only .001 of atmospheric pressure, the phenomenon was called a Tunnel Micro Pressure Wave. The air exited in low-frequency waves (under 20Hz) that produced a large boom and aerodynamic vibrations. Neighbors from as far away as 400 meters from the tunnel exit were complaining and this was preventing the team from testing the train at speeds greater than 350 km/hr.

This problem was particularly troublesome because it was tied to both the geometry of the tunnel and the speed of the train. The micro pressure of the wave was in proportion to the ratio of the cross-section of the trainset to that of the tunnel. Moreover, every unit increase in speed was producing an increase in pressure to the power of three.

The team was stuck with the tunnel geometry: Japanese Shinkansen tunnels average 64 square meters (compared with more than 80 square meters of the typical European tunnel) and could not be easily rebuilt or retrofitted. Although special hoods had been devised and fitted to some tunnel entrances, this was expensive and slow work that yielded marginal results. Likewise, the width of the track would have to be a “given” and this would limit any change in the train body . The train width of the Shinkansen, which is just under 3.4 meters, is the widest in the world in order to seat five in a row in second class. They would have to find a way to redesign the shape of the train to go faster without creating the boom. The key was in preventing the pressure wave buildup by reducing the cross-sectional area of the train and redesigning its nose.

The Inspiration: the Kingfisher

A discussion with a junior engineer prompted Mr. Nakatsu to once again search for the answer in nature. The young engineer had observed that the test train seemed to “shrink” when it was entering the tunnel. Nakatsu reasoned that it must be due to a sudden change in air resistance, from open sky to closed tunnel, and wondered if there was an organism that was adapted to such conditions.

Reynolds numbers and turbulence, for example. Factors like manufacturing methods, materials and costs could be added to the analysis to determine shape changes.

The CFD simulation would be able to depict more than just the effects of the train shape in order to solve the problem. In the case of the sonic booms, the tunnel, another passing train and the exits could all be modeled in order to observe the effects of different configurations on airflow, and therefore turbulence and noise. While Autodesk does not offer an acoustical simulation option, designers could predict relative noise levels using surrogates such as Reynolds numbers.

By now the designer would have tested hundreds, rather than dozens of configurations at a fraction of the time and cost and be ready to take the top candidates on to physical testing. Bring on the wind tunnel!

We would like to thank Carolyn Rohrer - Public Relations Manager, Sustainability, Autodesk - for her coordination and support in making the interviews with Mr. Nakatsu and Mr. Mihelcic possible

Composite of pied kingfisher diving (*Ceryle rudis*)

Photo: Dr. Stephen Nawrocki, 2009 | Flickr cc

From his bird watching experiences, Mr. Nakatsu remembered the kingfisher, a bird that dives at high speed from one fluid (air) to another that is 800 times denser (water) with barely a splash. He thought that the animal was worth closer study and surmised that it was the shape of the bill that allowed the bird to cut so cleanly into the water.

The Design Process

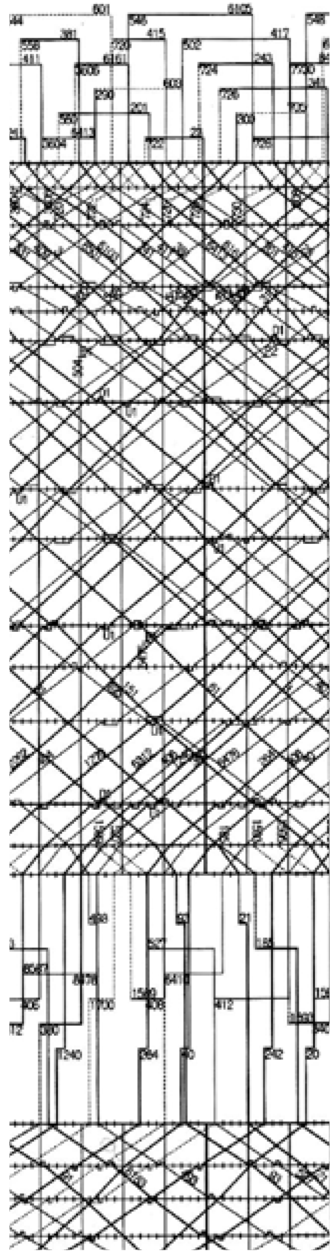
The train then in service, the Shinkansen 300 series, had a more or less wedge-shaped nosecone, having supplanted the earlier bullet-nosed trains. This was compared with new alternates by the use of scale models.

All of the Shinkansen companies were attempting to solve the sonic boom problem and RTRI made an intensive investigative effort. They found that the ideal nose was either a wedge or a rotational parabolic body with a section that changed area by a constant ratio.

As with the owl, the JR West team obtained the natural artifact and analyzed its dimensions and materials. What Mr. Nakatsu found was that the bill of the Kingfisher was consistently round in cross-section, and he described it as "a circular lozenge surrounded by four circles". The Kingfisher bill can also be described as a rotational parabolic body. Both the upper and lower beaks of the bird have triangular cross-sections with the sides of the triangles being curved. Together, they form a squashed diamond shape; the same shape that would be formed in the interstices of four perfect circles packed together.

Informed by these parameters, RTRI set about to test various nose shapes in a to-scale model tunnel and measure the pressure waves generated. They shot bullets of various shapes into a pipe, from the more traditional bullet nose to sharper shapes, including that of the kingfisher bill. Concurrently these same shapes were run in simulations on a space research supercomputer. A train nose very similar to the bill of the kingfisher was then selected.

All the tests confirmed what could be observed in real life: the shape of the Kingfisher bill was, indeed, the most efficient of all those test-



Shinkansen timetable

Photo: kerim, 2005 | Flickr cc

N700, 700, 500, 300, 100, 0 Series | Hakata Depot JR-West, 2011

Photo courtesy of Nakatsu, Eiji

ed, besting all alternates by a wide margin. Refined prototypes were built and ultimately made to full-scale for test runs on the tracks.

It was at this point that Mr. Nakatsu became convinced that nature had much to teach about efficient forms. His initial inspiration had been confirmed by the results of both the large scale instrument tests and the analysis of the supercomputer. In a dramatic 2004 demonstration of the streamlined quality of the kingfisher beak, TV Asahi broadcast a program showing the differences in splash created when a simple cone and a rotational parabolic body are each dropped into water.

The Solution

The new 500 series train design comprised a lengthened nosecone of 15 meters (compared with 6 meters for the 300 series) and a more rounded body. The 300 series train body was also redesigned; fared top and bottom from the required basic width, thus reducing the section area to 10.2 square meters from the original 11.4 square meters.

The design reduced the sonic boom effect, and allowed the train to run at 300 km/ hr and still adhere to the standard noise level of 75 dB(A). It also reaped further benefits immediately. The new Shinkansen 500 was faster, quieter, and had more power, and yet it had 30% less air resistance than its predecessor. Energy consumption was reduced proportionally. A measured actual train run (maximum 270 km/hr) showed a 13% reduction in the power that had been needed by the 300 series.

On March 22, 1997, JR-West put the 500-Series Shinkansen electric train into commercial service. The train was able to run at 300km/h at its maximum, a world speed record at the time, and meet the stringent noise standard. Traveling time between Shin-Osaka and Hakata had, as the company had challenged, been shortened, from 2 hours and 32 minutes taken by the conventional 300-Series "Nozomi" train to 2 hours and 17 minutes. In November of that year extended service by the 500-Series trains to Tokyo was offered, with three round trips a day, increased to five in March, 1998, and seven in 1999. The fastest of these trains was able to make the 1,069 km distance in 4 hours and 49 minutes.

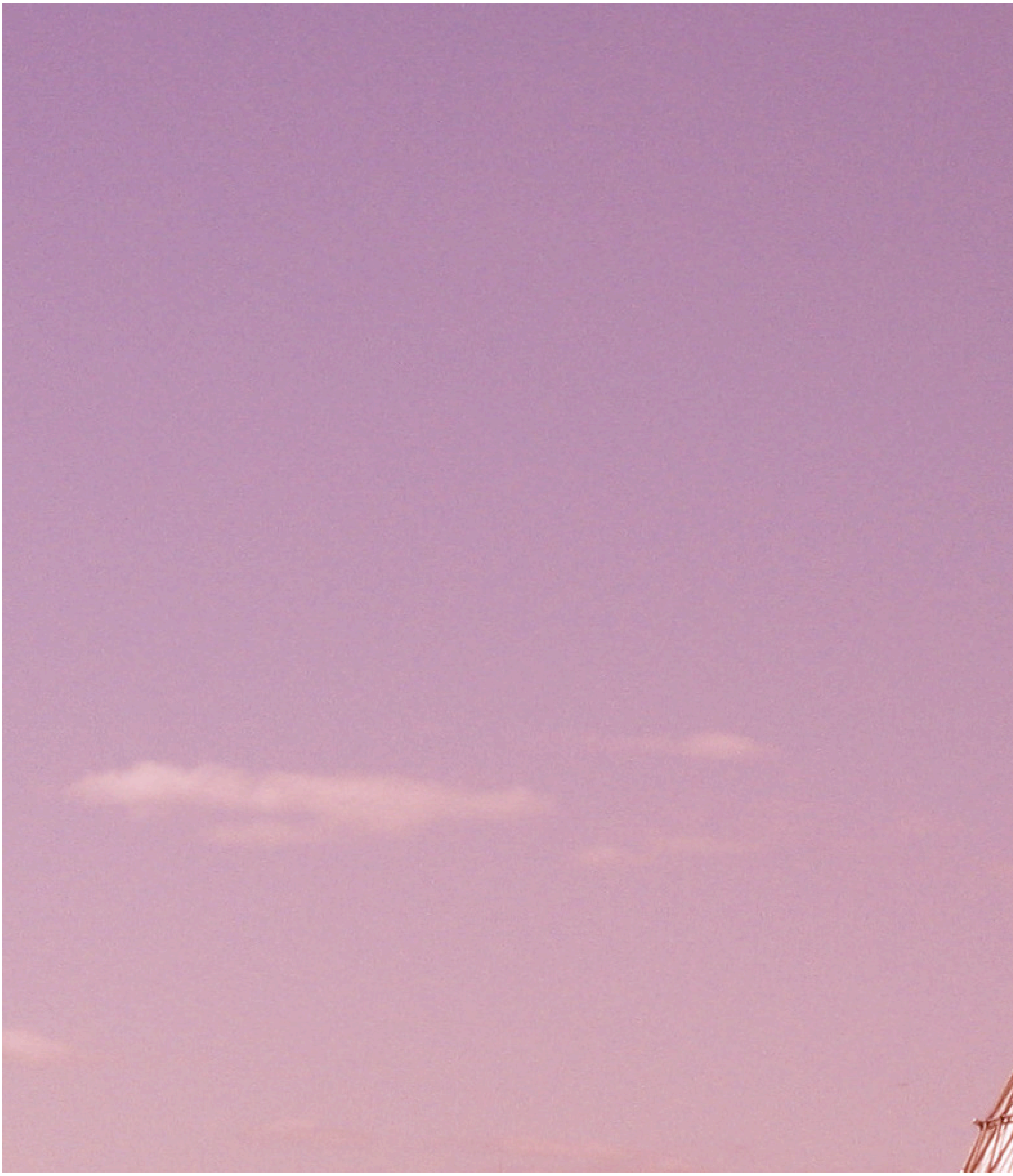
For Mr. Nakatsu, the little notice in the Osaka newspaper had been the start of a long fascination with the lessons that nature has to teach. "...I was struck by the amazing functions that had been developed by living things. I learned first hand that truth can be found in the way life exerts itself in order to persist and carry on in this world. From then on, 'learning from nature' became a recurrent theme for me." His realization was to be auspicious for us all. ×

Eiji Nakatsu was the General Manager of the Technical Development Department of Japan Railway West from 1989 to 1992, and General Manager of the Test Operations Department of JR West from 1992 to 1995. From March, 1992 to June 1995 he supervised all the running tests of the WIN350 test train. He is currently a technical advisor to the Japan Railway Technical Service (JARTS), and the vice Executive Director of the Kinki Environmental Citizen's Supporting Center.

500 Series and Nakatsu, Eiji at Hakata Station

Photo courtesy of Nakatsu, Eiji

Snowy Owl Flight #2 | Photo: {ErinKphoto} aka redcargurl, 2012 | Flickr cc



Geodesic

Photo: 416style, 2006 | Flickr cc

Two Perspectives
Bucky, Geodesics and Biomimicry

Jay Baldwin

summer 2012

Two Perspectives:
Bucky, Geodesics and Biomimicry

Author:
Jay Baldwin

Bucky, Geodesics and Biomimicry

"Biomimicry", coined by Janine Benyus in her 1997 book of that name, has become a rather loosely-defined term. I think the simplified definitions and many subsequent examples of it by other writers are too restrictive. I prefer to think of the term in an inclusive way, for it is too soon to saddle a recently-accepted principle with rigid exclusions. These exclusions invite "counting the angels-dancing-on-a pin"-types of arguments. Thus, I consider Boeing Company's 747 airliner to be a useful example of biomimicry.

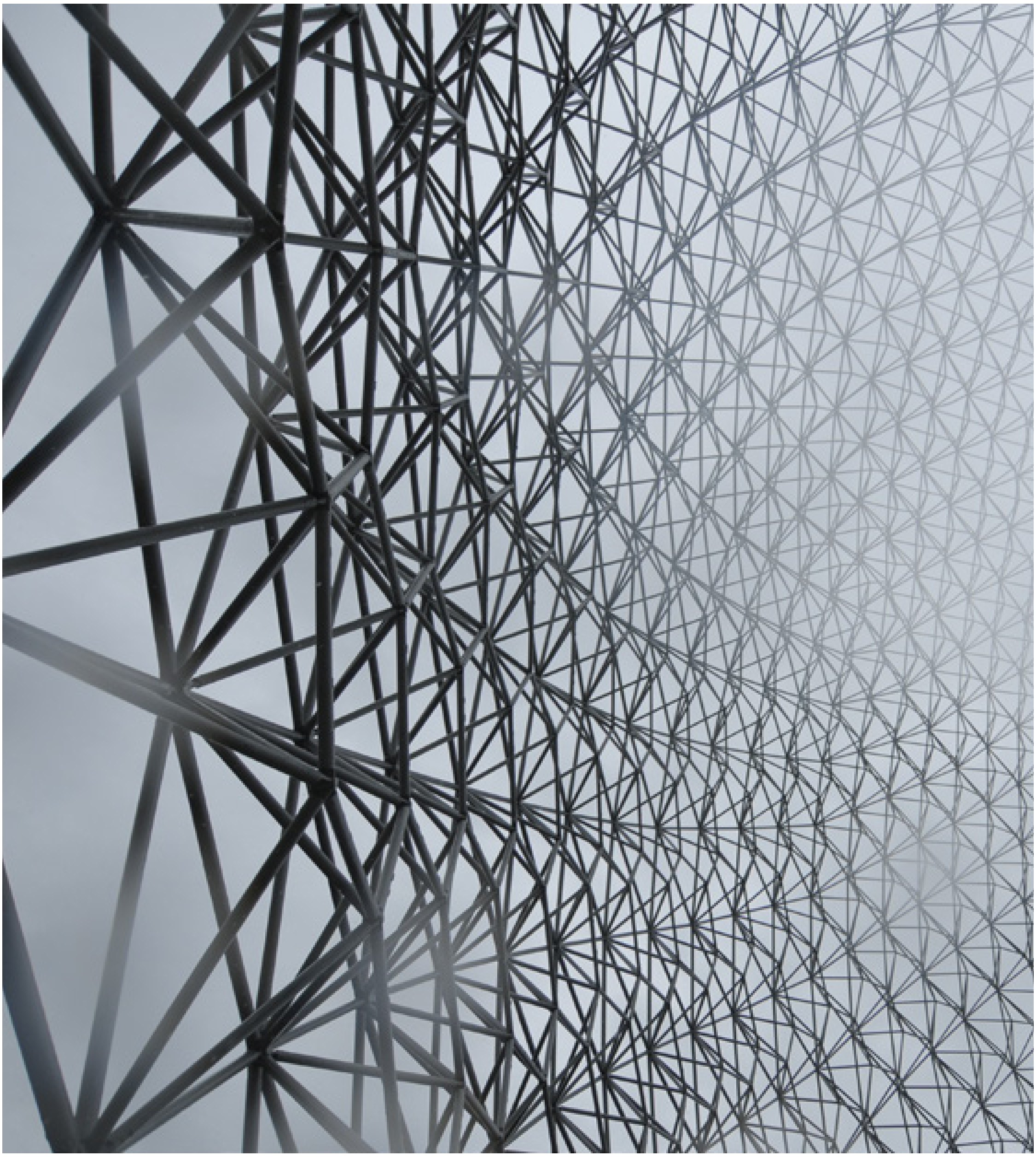
Boeing's designers measured the efficiency of certain birds while seeking a model for the design of the 747. While they did not intend to mimic a hummingbird by having the 747's enormous wings flap like a bird's, the 747's lift-to-drag ratio (known as the "finesse") is about the same as a hummingbird's. In flight, they both consume about 3% to 4% of their takeoff weight per hour. (How a hummingbird can cross the Gulf of Mexico without refueling remains a partial mystery).

Synergy

Buckminster (Bucky) Fuller taught that "evolution makes many starts", and that Nature has always evolved life forms to be an optimal solution to the environmental conditions involved. To use his lingo, all life forms are synergetic. Bucky defined synergy as the condition in which an examination of the parts or subassemblies of parts gives no hint of the performance of the whole. One of his favorite examples of synergy was the tensile strength of chrome-molybdenum steel, commonly specified by designers of racing bicycles. The tensile strength of "Chrome-moly" is far higher than the added-up tensile strengths of the metals included in that alloy. Bucky also noted that the advantage-giving metallurgy is invisible to humans unaided by instruments. He suggested that computers would probably not be able to detect, much less predict, synergy because there was yet no way to program them to do so. Thus, synergy remains, essentially, unpredictable.

Human designers rely commonly on trade-offs, negotiation and compromise to inform their design decisions. Worse, they often employ (and regrettably, often teach) "benchmarking": a tactic in which a market-successful design is copied as closely as possible without incurring a lawsuit. A small change is usually made, so that a claim of 'new' can be used. But such designs, so deeply inspired by the past, are not new at all. In fact, benchmarking ensures that evolution will be artificially delayed, that true innovation will come slowly if at all, and that any advance will likely be minimal. I regard such tactics and terms as being political, rather than biomimetic. Nature has no politics, but of course sometimes votes "NO" when the laws of biology, chemistry and physics are ignored.

Because Nature does not recognize markets, all life forms have been developed over time to be



Biosphere

Photo: T03, 2011 | Wikimedia Commons

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Two Perspectives:
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Geodesic in nature: Dragonfly Eyes

Photo: kaibara87, 2010 | Flickr cc

Geodesic in nature: Female Jumping Spider (eyes)

Photo: Thomas Shahan, 2009 | Flickr cc

Bucky + 30 foot wood and plastic geodesic (marines flew the dome at 50 knots without damage), 1954

Photo: dodeckahedron, 2007 | Flickr cc

optimized to deliver the best performance possible, considering all aspects of their existence as part of a system. That is, a pelican is the best possible pelican at this time. An improved pelican would soon become the pelican, or a new life form that takes the place of the present pelican, as conditions change.

Note that I am not merely referring to mechanical efficiency. When an insect lays thousands of eggs, with little hope that many will survive, it is, nonetheless, being "efficient" if you keep in mind that the multiple-egg strategy is the only way to prevent species extinction. Over time (sometimes a very long time) the great number of interlocking strategies by many millions of life forms has resulted in the relatively stable populations and huge number of varieties we see today. Every member is in a state of slow change that subtly adjusts the balance of the system in which it is embedded. The interactions ensure that Co-Evolution is common: the evolutionary changes in the beings induce changes in their surroundings and associated beings as the system adjusts into an uneasy balance that assures its continuity.

Geodesics

Unlike many biologists, Bucky insisted that his "energetic-synergetic geometry" was 'natural' in the sense that it was there, all worked-out, as a mathematical principle employed by Nature to give optimum advantage to the system. Bucky did not claim that he invented geodesics, but he claimed that he had discovered, or was the first to recognize, geodesic advantage.

The word, geodesic is a navigator's term for the most direct, energy-efficient line between two points on the surface of a sphere. A geodesic dome made of tubing has a tube (strut) connecting two points of the dome's surface, which has the effect of triangulating the dome in every direction. This feature gives a geodesic dome its superior strength.

Where does Nature use geodesics? Your eyeballs are geodesic. So are your testicles (if you are so equipped) and breasts. If you inspect a common balloon or a chicken egg or bird bones under a scanning electron microscope, you will see the familiar assembly of triangles as a net with triangular openings small enough to contain air molecules and a variety of compounds. Bucky expected, but could not prove during his lifetime, that atoms would turn out to be geodesic structures. What else could they be? He did prove that Nature could not be using Pi, because the area of a circle, calculated by using Pi times radius squared, is an irrational number.

Irrational Reality

The same problem arises when calculating the surface area and cubic volume of domes. Bucky asked, "How can you have irrational reality? Is Nature making fake bubbles?" He went on to show that 90-degree, three -dimensional x, y, z, axis calculations commonly used in physics and mathematics are inevitably inaccurate as physical reality and in theory as well. Nature works in 60 degrees, a radical theory now accepted by many top geometers.

Geodesic math includes time as a fourth dimension. Calculus is not useful in calculating geo-

Summer 1949 from the Black Mountain College Research Project Papers | North Carolina State Archives

desics; spherical geometry and finite vector analysis are. I am not a mathematician, so when geodesic strength calculations are needed I have the finite vector math done for me rather than risk performing an inaccurate procedure I don't use often enough to be reliable.

Biological organisms generally use energy in the most (overall) efficient way, and geodesic designs arrange their components in the most energy-efficient way. Most of Bucky's domes use the geometry of the icosahedron, a sphere-related solid consisting of twenty identical equilateral triangles meeting at pentagonal nodes. It is a self-organizing figure, another example of minimizing energy expenditure. Thus, a well-detailed geodesic dome can offer the most efficient use of materials, assuming the designer chooses appropriate materials of suitable dimensions.

A Chilling Machine

A geodesic dome—already the strongest structural system known—is also the only structure known that gets stronger as it gets bigger. Indeed, there is no limit to their diameter and height. Bucky calculated domes several miles in diameter, insisting that they were perfectly feasible. One of his most notorious proposals was a 3-mile diameter dome over Manhattan. That dome would pay for itself by eliminating snow removal costs and reduced wind chill in winter. With appropriate detailing of the vents, the dome would act as a "chilling machine" able to cool itself in summer sufficiently to eliminate the need for air conditioning individual buildings. Of course combustion would not be permitted under the dome; necessary vehicles would be electric, which would improve air quality. The sun would provide the necessary space heating. Air quality would also be better because domical spaces (which need not be geodesic to support this phenomenon) do not stratify thermally: the air temperature at the peak will be the same as at the floor and everywhere in between. (I was skeptical when Bucky made this claim, but observing 19 matching lab-standard thermometers hanging from the apex of a dome proved him right.) No fans are needed, for domes constantly circulate their interior air naturally, moving it in a toroidal pattern rather like a smoke ring or nuclear explosion. The even distribution of temperature reduces the need to add the additional heat to warm the lower volume of conventional rectangular buildings in which the heated air tends to rise as far as it can and then sit there until it stagnates. The natural circulation in domes is also much less drafty. In a greenhouse, the natural air movement brings fresh carbon dioxide the plants, encouraging them to grow stronger and more quickly.

Larger dome sizes, require an increase of the dome's frequency, that is, increasing the number of triangles by dividing larger triangles with heavy components into more and more smaller triangles with slender components strong enough for the loads they must handle. Building this way results in a dome that is omnitriangulated, that is, triangulated in all directions. This arrangement almost instantly distributes applied forces evenly around the dome. Distributing local loads over the whole dome protects individual components from dangerous concentrations of stress. Structural earthquake damage is no longer a threat. Most geodesic domes use pentagonal geometry. Pentagons contain many instances of the "golden proportion", the same proportional system thought to have been used in the 2400 year-old Parthenon, and many natural Fibonacci spirals such as those seen in sunflower seed heads, for instance. Since ancient times, humans have found that those proportions are deeply pleasing to the eye and mind.

The foregoing discussion shows that human use of Nature's geometry and strategies for energy efficiency is certainly an example of biomimicry. Bucky Fuller did not use the term, "biomimicry", (it had not been recognized during his lifetime), but he certainly did seek, to understand and utilize the principles employed by Universe. His domes are just one example of what can be done when natural forms and materials are used in the most efficient and elegant way. ×

Summer 1949 from the Black Mountain College Research Project Papers

North Carolina State Archives

Larch: female flower

Photo: Bushman. K, 2010 | Flickr cc

People
Interview with
Thomas Knittel

Project Haiti Courtyard

Courtesy of Thomas Knittel and HOK

Interview

Thomas Knittel

Thomas Knittel is a vice president in HOK's Seattle studio and a former design principal and strategic director of sustainable design in HOK's New York studio. His former international projects include the LEED Platinum KAUST (King Abdullah University of Science and Technology) in Saudi Arabia, the Commonwealth Medical College in Scranton, Pa., a mixed-use center in Wuhan, China, and a bio-inspired commercial center in São Paulo, Brazil.

Thomas donates his time as HOK's design leader for Project Haiti, a Port-au-Prince orphanage and children's center funded by the USGBC. His work explores the intersection of biology, ecology and the built world, including the recently completed Genius of the Biome report, a collaborative effort of Biomimicry 3.8 and HOK. He has received more than 29 awards, including a GSA Design Excellence Award and an AIA Top Ten Green Projects award for KAUST. Thomas holds a Master in Design Studies from the Harvard Graduate School of Design.

What are your impressions of the current state of biomimicry/bio-inspired design?

It is still a new frontier. Janine Benyus recognized by the Cooper Hewitt is a pretty good sign it is coming into its own.

What do you see as the biggest challenges?

The way we make things. Nature builds from the bottom up, and we build from the top down. A designer has an idea of what something should be, and then shops for parts. This is oversimplified, but emergent systems are open to chance yet mostly seeking refinement.

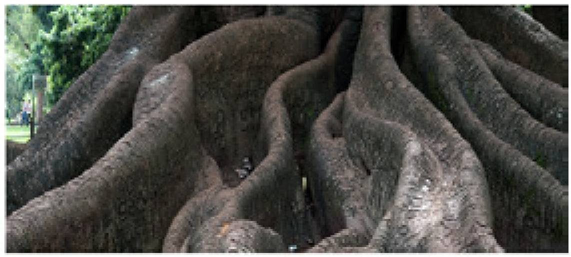
How can we slow down the rate of planned or unplanned obsolescence, which in biological terms are dead ends, and instead create solutions that accrue intelligence over time? Changing the way we make things is the greatest challenge, because heat, beat and treat is still the fastest and cheapest way. In a perfect world we would be able to reshape everything we need from a common set of benign materials, from breakfast bowls to car fenders fabricated in water at room temperature. Structural gradients will occur where parts need flexi-bility or hardness or resist torsion.

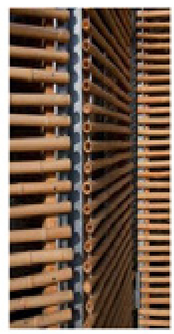
What areas should we be focusing on to advance the field of biomimicry?

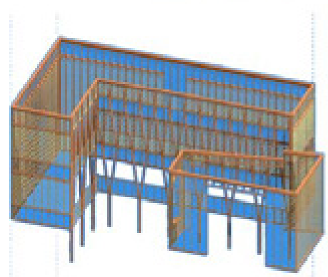
We have been accustomed to understanding things at the human scale, which is natural. Focusing on the dimensions of scale unfamiliar to us, from the nano to the macro is where the new territory lies.

How have you developed your interest in biomimicry/bio-inspired design?

My interest started about ten years ago when I started to work with landscape ecologists within the context of urban planning. When I joined HOK in 1997 I started to work with the Biomimicry Guild (now 3.8) and finished their Biomimicry Specialty program last year, which has been an interesting balance of practice and education.







Project Haiti

Courtesy of Thomas Knittel and HOK

Project Haiti Aerial | Courtesy of Thomas Knittel and HOK

What is your best definition of what we do?

Stepping outside of convention is great for the curious mind.

By what criteria should we judge the work?

I was hoping you could tell me! I have always believed good design needs to operate at multiple levels. Bio-inspired solutions that don't inspire us will not survive.

What are you working on right now?

I am finishing an orphanage and family center in Haiti that was destroyed in the 2010 earthquake. Our HOK team has been working pro bono, which is extremely gratifying yet very hard to do. It is a project of the US Green Building Council, who took up the challenge and invited us to design to its highest standard, LEED Pla-tinum. It goes beyond this out of purpose and necessity. Water is trucked in, and electricity comes from diesel generators in Port au Prince. We are adhering to best practices and international code building standards. Bio-inspiration is in the variable second skin forming a building boundary layer to reject heat and harness na-tural ventilation. A wooden branching support structure facing the courtyard is based upon patterns in nature and observed by da Vinci and Fuller and, more recently, Bejan's constructal law. I will admit our solution is not pure, but it serves the building functionally and metaphorically. What better place to display mother-daughter branching?

How did you get started in biomimicry/bio-inspired design?

Before I entered architecture school I was building string and rod tensegrity models and drawing seedpods as architecture, so I guess I have come full circle.

Which work/image have you seen recently that really excited you?

Christine Ortiz at MIT has created amazing animations exploring the range of motion of armored fish, such as the Stickleback. The potential applications are really exciting.

What is your favorite biomimetic work of all time?

Selfishly, the project I designed in Brazil. After two years of work, it will not be built for economic reasons.

What is the last book you enjoyed?

Design In Nature by Adrian Bejan

Who do you admire? Why...

Janine Benyus for inspiring people.

What's your favorite motto or quotation?

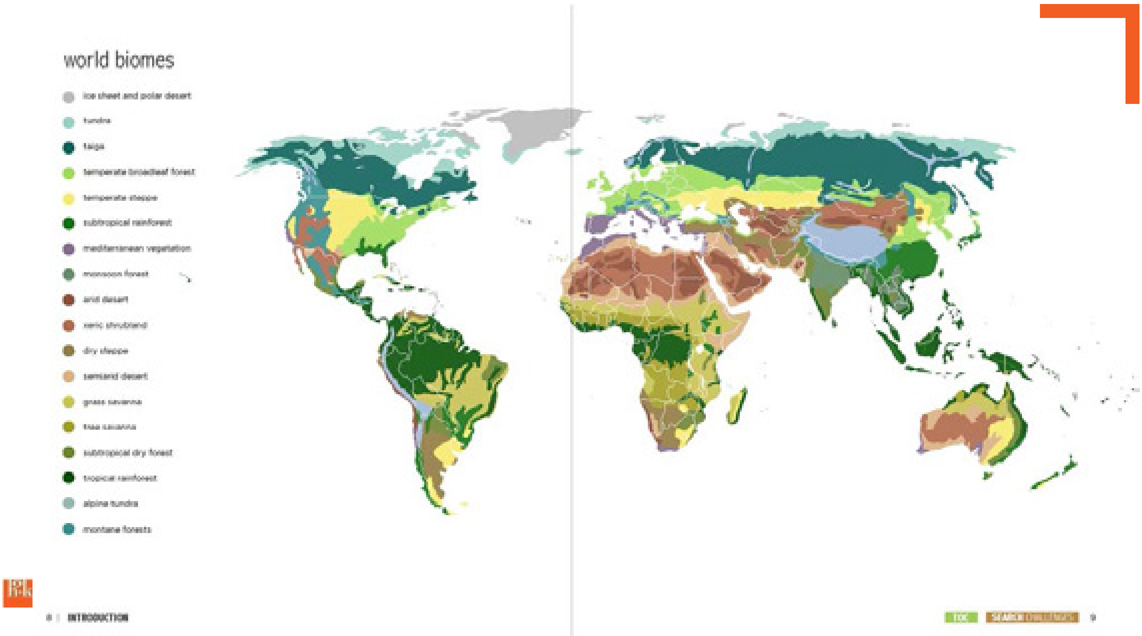
'The best of artists has no conception that the marble alone does not contain within itself.' – Michelangelo. I like the idea of limitless possibility.

What is your idea of perfect happiness?

No distinction between work and pleasure.

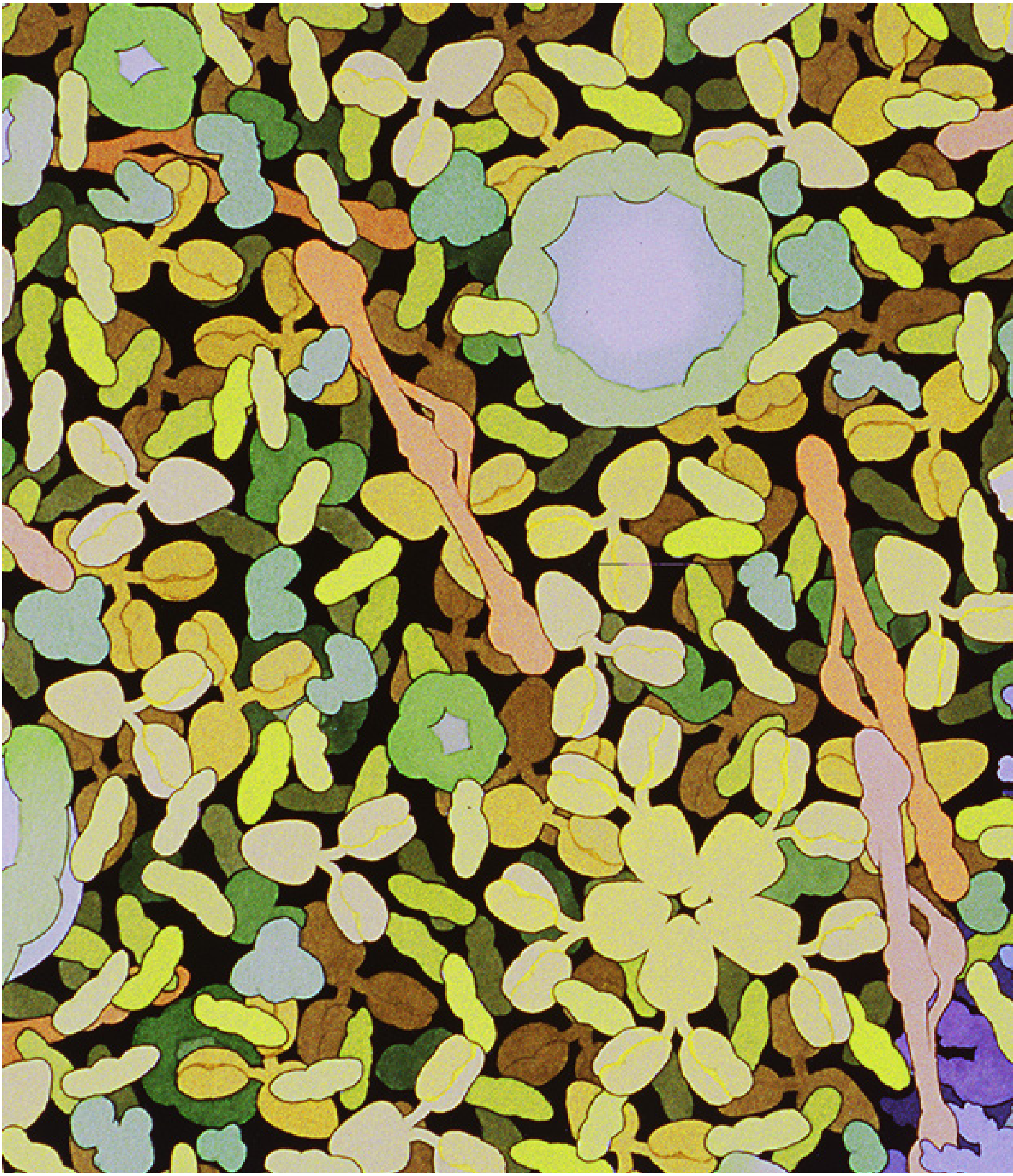
If not an architect, who/what would you be?

If I were to start over I would be a bio-inspired scientist because it is where the action will be.×



Genius of Biome design resource and innovation tool, co-authored by Biomimicry 3.8 and HOK

Courtesy of Thomas Knittel and HOK



Blood: This illustration shows a cross-section through the blood, with blood serum on the left and a red blood cell on the right. In the serum, look for Y-shaped antibodies, long thin fibrinogen molecules (in light red) and many small albumin proteins. The large UFO-shaped objects are low density lipoprotein and the six-armed protein is complement C1. The red blood cell is filled with hemoglobin, in red. The cell wall, in purple, is braced on the inner surface by long spectrin chains connected at one end to a small segment of actin filament.

Portfolio

David Goodsell

David S. Goodsell is an Associate Professor in the Department of Molecular Biology at the Scripps Research Institute in La Jolla, California.

Could you tell us about your background and how you got started in the field of illustration?

I've drawn and painted since I was a kid. My grandfather was a watercolorist--he did beautiful and bold landscapes. He got me started when I was still in elementary school--bought me my first set of paints and a palette that I still use for every painting. I started scientific illustration in graduate school. I was lucky to have Richard Dickerson as my graduate advisor. He has a long history of combining art and science, most notably in his collaborations with Irving Geis. In his lab, I was able to develop new techniques for using computer graphics to visualize the DNA structures we were solving. It was an exciting time, right when computer graphics was new and everyone was trying to come up with effective ways to use the new technology.

What kind of techniques do you use for your work? What are your tools of the trade, both hardware and software?

My current style combines computer graphics and hand-painted watercolors. For individual molecular structures, I use a program that I developed as a postdoctoral student with Art Olson, that renders molecular structures in a cartoony style, with outlines and bright colors, but without a lot of the highly-rendered highlights that are often used in computer graphics. For more complex scenes, like the cellular environments, I use watercolor, creating a painting based on the atomic structures and as much biological data as I can find about the topic.

How has your art/style changed since you first started?

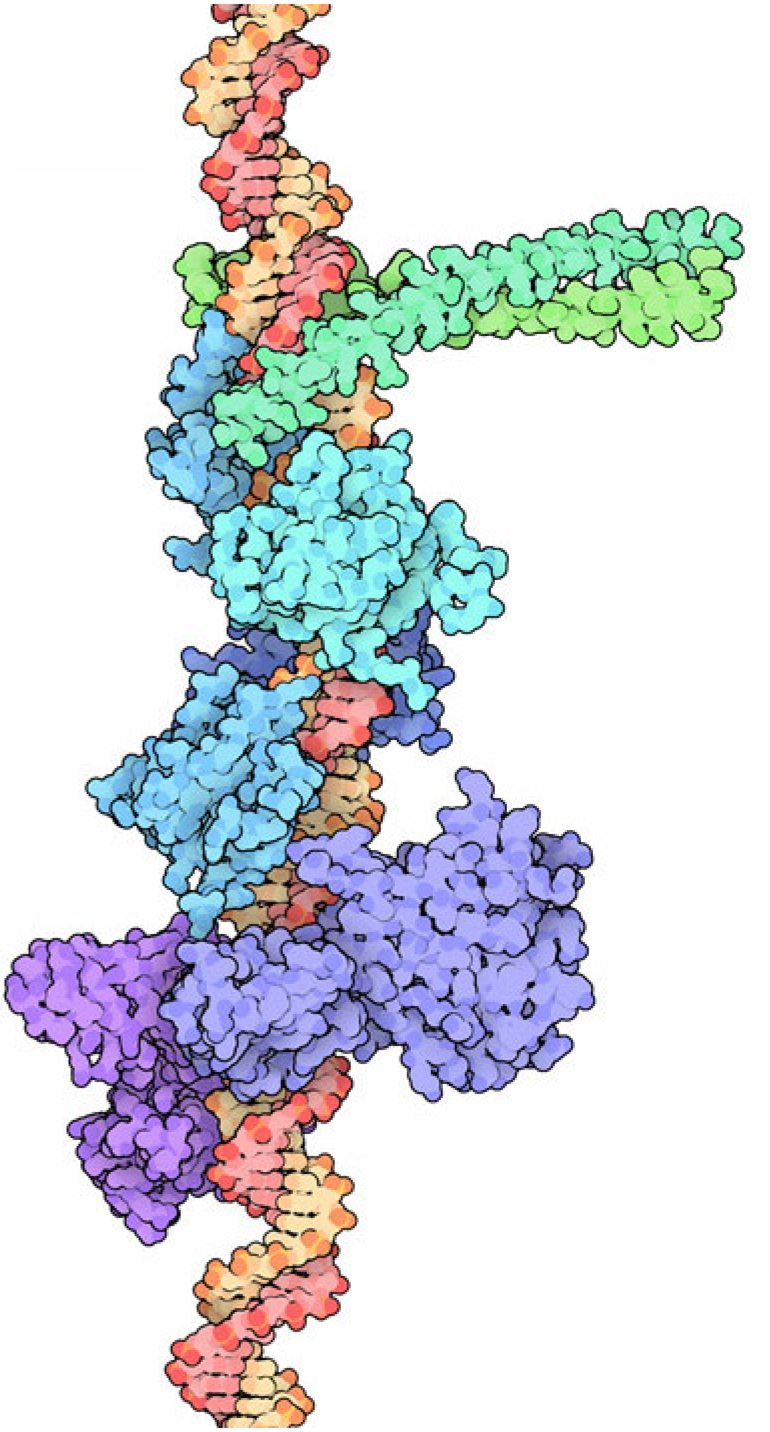
Quite a lot! When I started in graduate school, I was very much seduced by the tools, using everything that was available. I developed all sorts of approaches for rendering atomic models and 3D data, using elaborate (and computationally expensive) rendering methods. In the past 10 years or so, however, I've toned down my style and tried to develop an approach that is clear and comprehensible, appealing, and also a bit more unique and personal.

How does your job as an artist and scientist influence your life? Do you feel that you see things around you differently for example?

I'm a big science nerd, so of course I don't see the world like a normal person. For instance, when I look at a flower, I immediately try to classify it and analyze its symmetry. And the artist in me is, at the same time, trying to decide how I'd frame it in an image. I suppose it adds extra texture to the world, constantly trying to unravel these connections...

How does your art influence your science and vice versa?

I'm lucky to be doing a lot of science outreach these days, with the RCSB Protein Data Bank, with TSRI, and with collaborators at



Enhanceosome: A collection of transcription factors (blues and greens) are bound to DNA (red and orange) to form an enhanceosome that controls the expression of the gene for interferon-beta, and important protein for fighting viral infection. This illustration, and the ones on pages 64-73, are taken from the Molecule of the Month series at the RCSB Protein Data Bank (http://www.pdb.org). The illustration was created using PDB entries 1t2k, 2pio, 2o6g and 2o61.

the Milwaukee School of Engineering. Much of my job is centered around using imagery (and writing) to bring the world of science to students and laypeople. In this work, there is a constant dialog between the art and science. The art is a way to make complex scientific topics accessible, in a way that is impossible otherwise. The science, on the other hand, provides a wonderfully engaging set of boundaries for the art: my illustrations need to be accurate and true to the science.

What are you working on right now? Any exciting projects you want to tell us about?

I'm working on an exciting collaboration with the Center for Biomolecular Modeling at MSOE, funded by a grant from NSF. In this project, they bring together a researcher and a group of students, and together we all design classroom materials to present a particular biological subject. I help by creating paintings about the subjects. I've done two so far: one on budding of vesicles and one just finished on signaling in the cells the surround blood vessels. I also love my work with the RCSB PDB. I get to learn about a new topic every month, and then create stories and pictures about it. It's really a dream come true to be able to work on this project.

What are your favorite 3-5 websites, and why?

The internet has revolutionized the way I do my scientific art, allowing me to make the pictures more and more accurate, by allowing me to find tons of experimental data. At the top of my bookmarks: the RCSB Protein Data Bank, PubMed, UniProt, and (slightly embarrassed) Wikipedia.

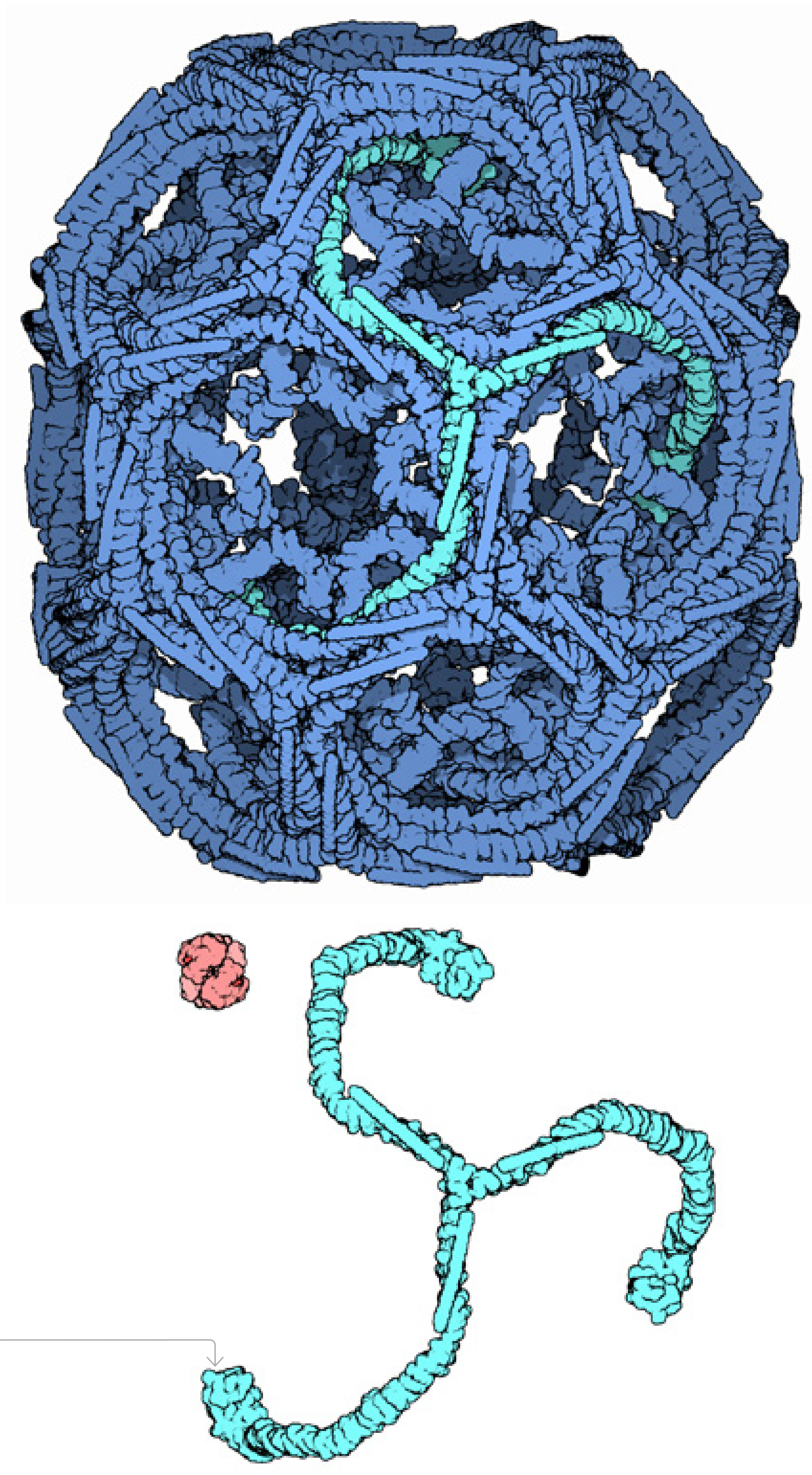
Who/what inspires you creatively? What do you 'feed' on the most?

So many things! When I want to get inspired, some of my favorite activities are going to an art gallery when I'm visiting other towns and getting out of the city and going on a hike. There are also several conferences that bring together artists and scientists, such as the Visualization in Science and Education Gordon Conference, Felice Frankel's Image and Meaning conferences, and more recently VizBi. These are an amazing way to meet creative people and share ideas.

What's your favorite motto or quotation?

"The important thing is to create. Nothing else matters; creation is all." - Pablo Picasso ×

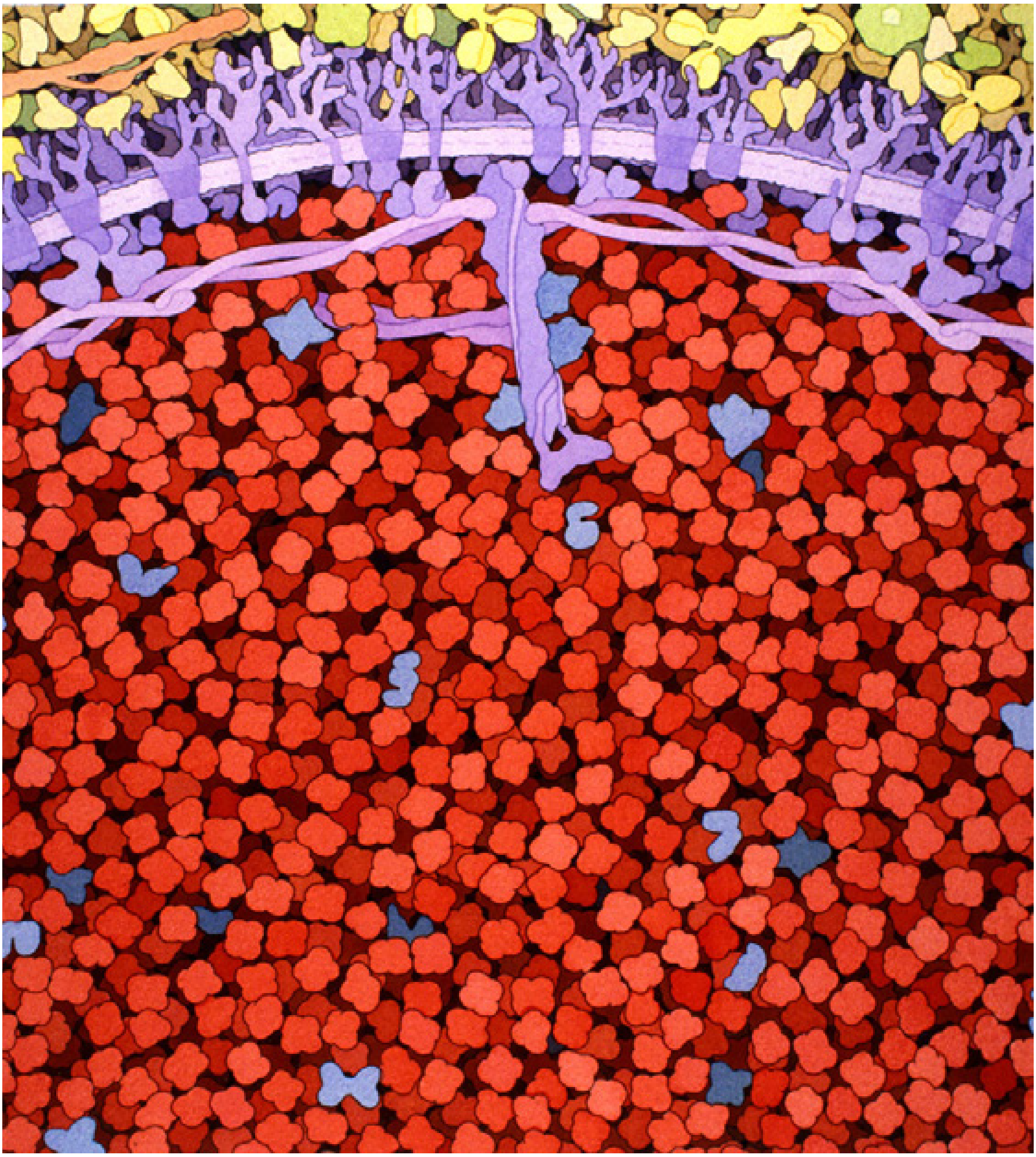
Structural Proteins | Clathrin: Clathrin is a perfect case of form following function. The long curved arms interlock to form a cage-like structure that shapes rounded vesicles for intracellular trafficking. A molecule of hemoglobin (red) is shown for size comparison. The illustrations were created from PDB entries 1xi4 and 2dhb.



summer 2012 **Portfolio**

Author:
David Goodsell

Cytoplasm: A small portion of cytoplasm is shown, including three types of filaments that make up the cytoskeleton: a microtubule (the largest), an intermediate filament (the knobby one) and two actin filaments (the smallest ones). The large blue molecules are ribosomes, busy in their task of synthesizing proteins. The large protein at bottom center is a proteosome.



Red Blood Cell: A portion of a red blood cell is shown in this illustration, with the cell membrane at the top, and lots of hemoglobin (red) at the bottom.

Author:
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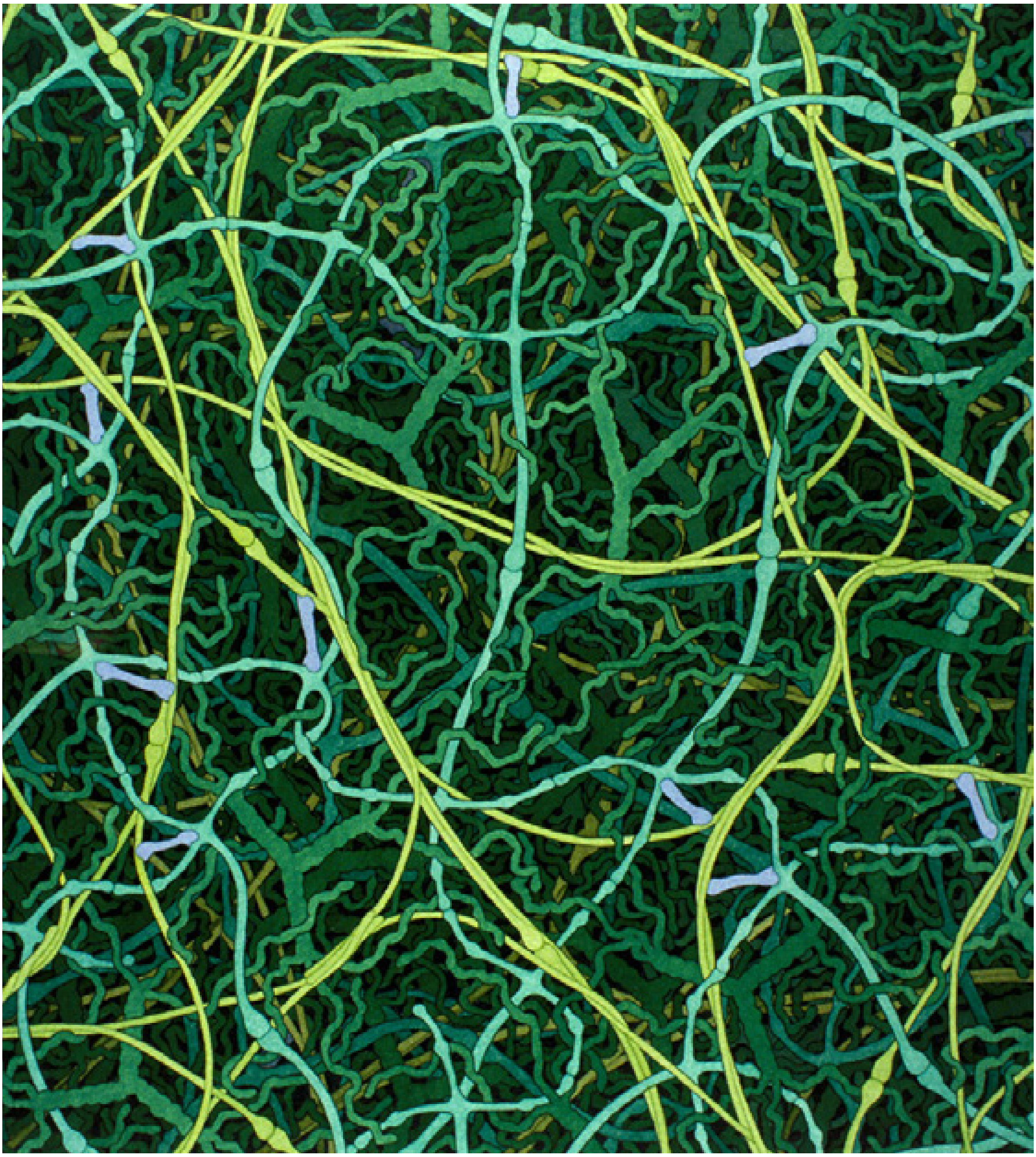
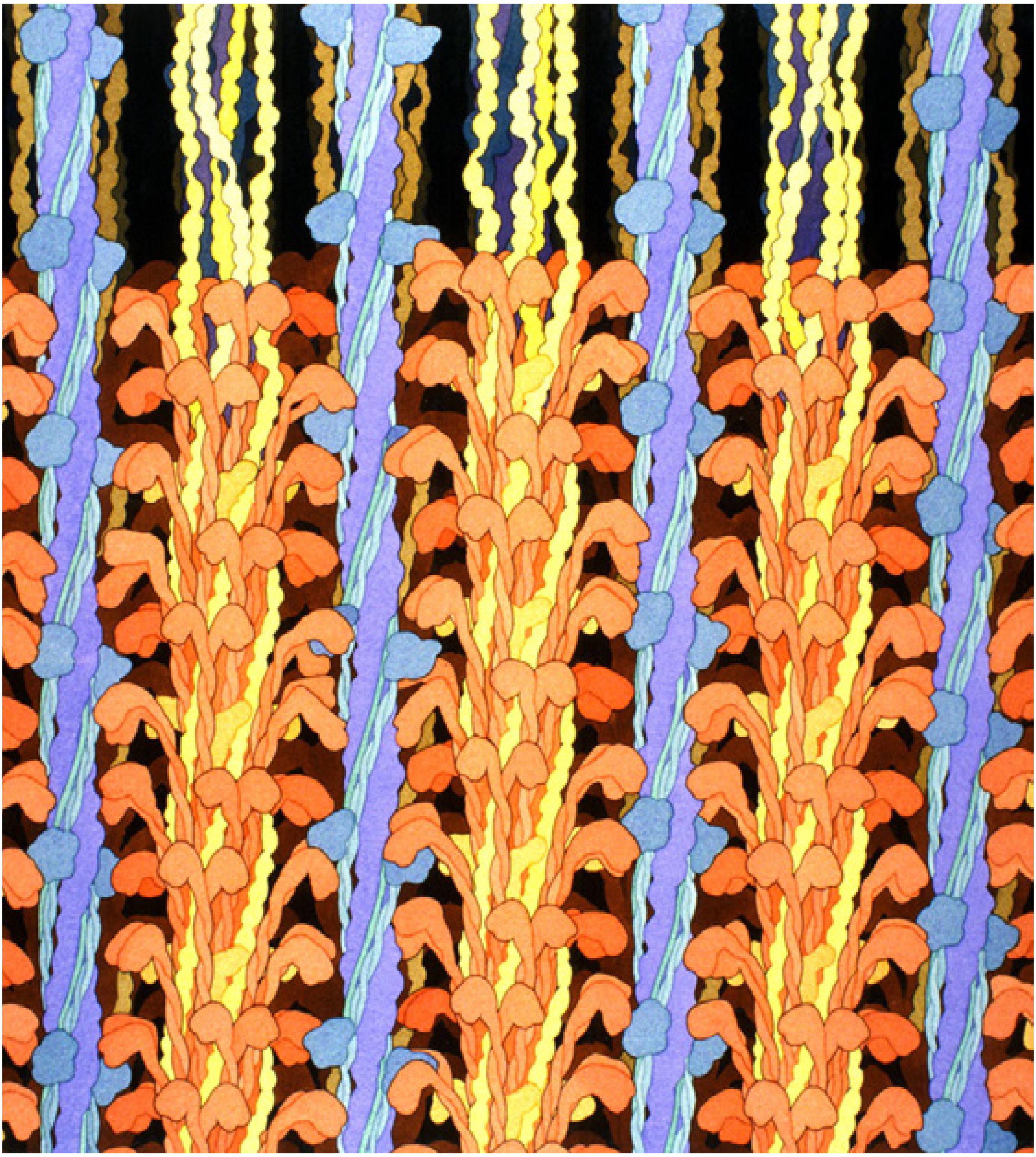
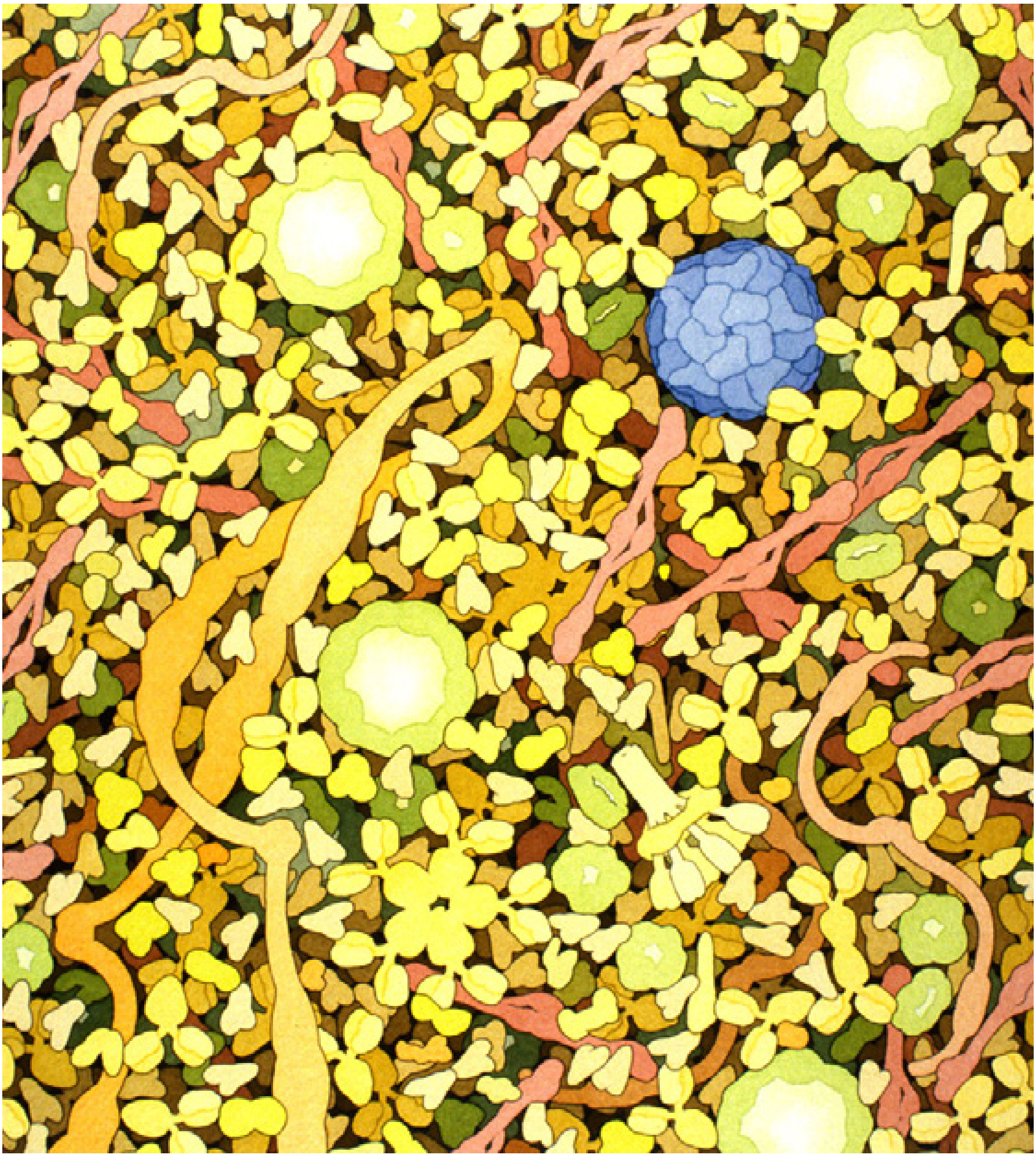


Basement Membrane: This illustration shows a portion of basement membrane, a structure that forms the support between tissues in your body. It is composed of a network of collagen (yellow green), laminin (blue-green cross-shaped molecules), and proteoglycans (deep green, with three arms).

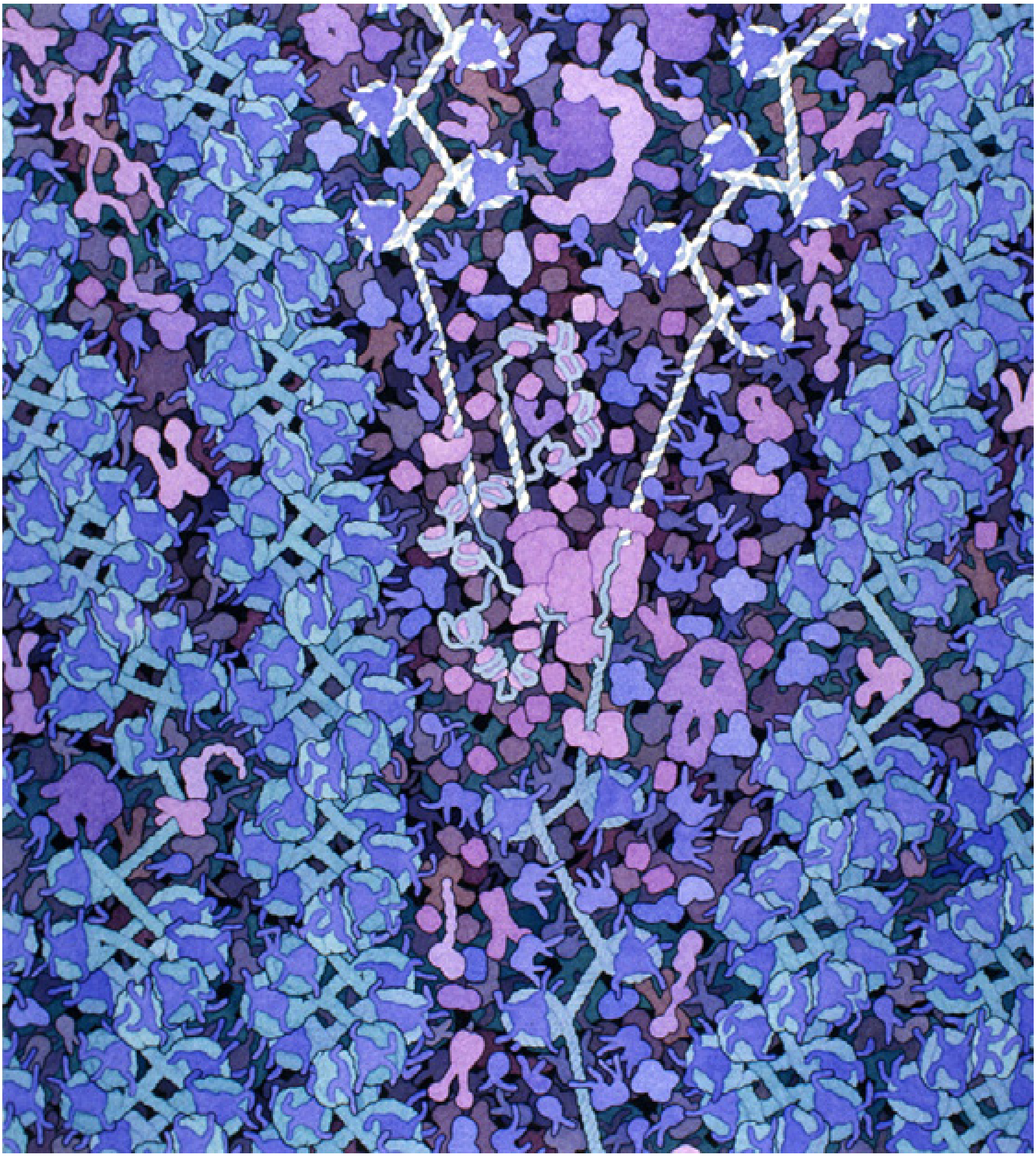


Muscle: Part of a muscle sarcomere is shown here, with actin filaments in blue and myosin filaments in red. The long yellow proteins are the huge protein titin.

Author:
David Goodsell

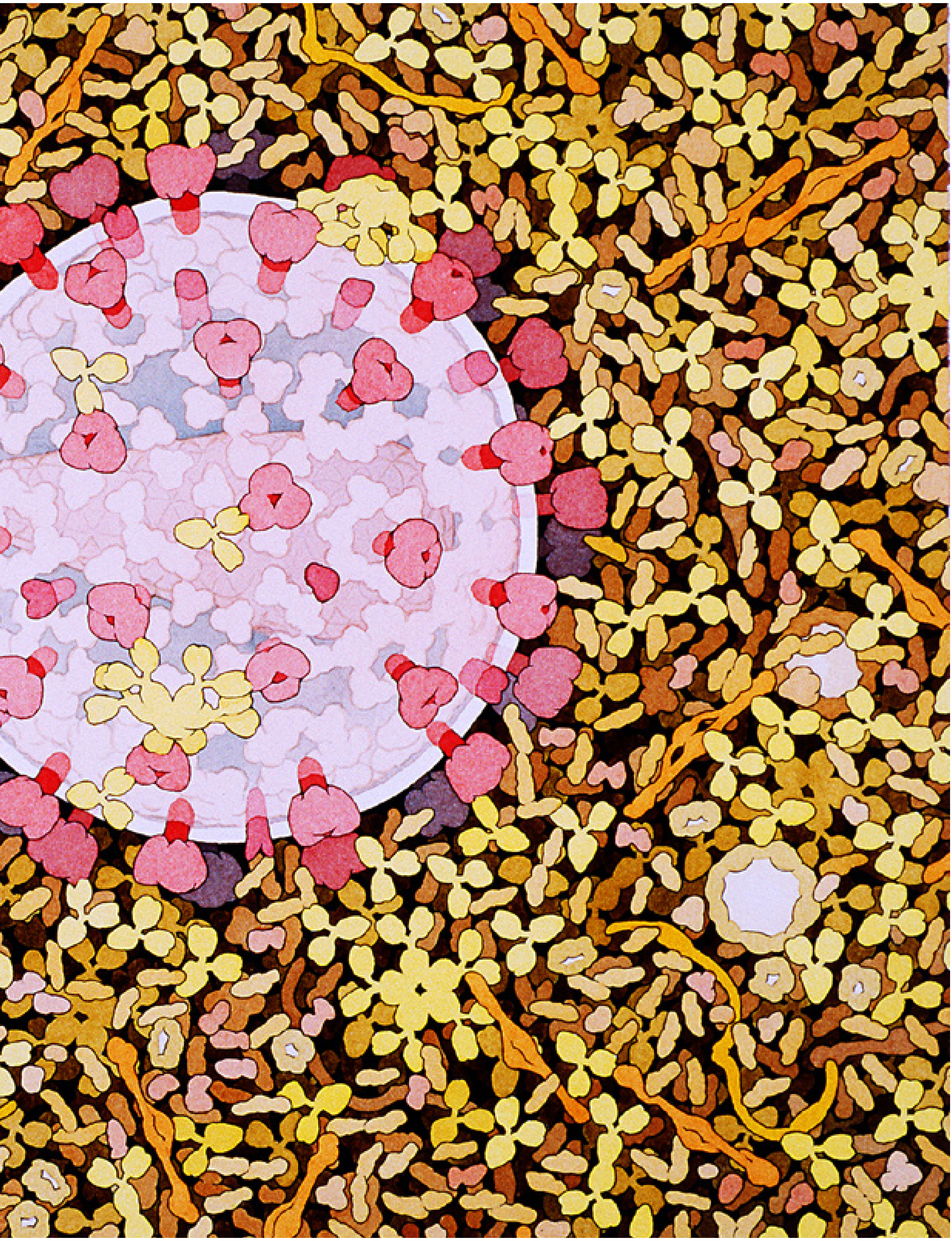


Blood Serum: Blood serum is shown in the picture, with many Y-shaped antibodies, large circular low density lipoproteins, and lots of small albumin molecules. The large fibrous structure at lower left is von Willebrand factor and the long molecules in red are fibrinogen, both of which are involved in blood clotting. The blue object is poliovirus.



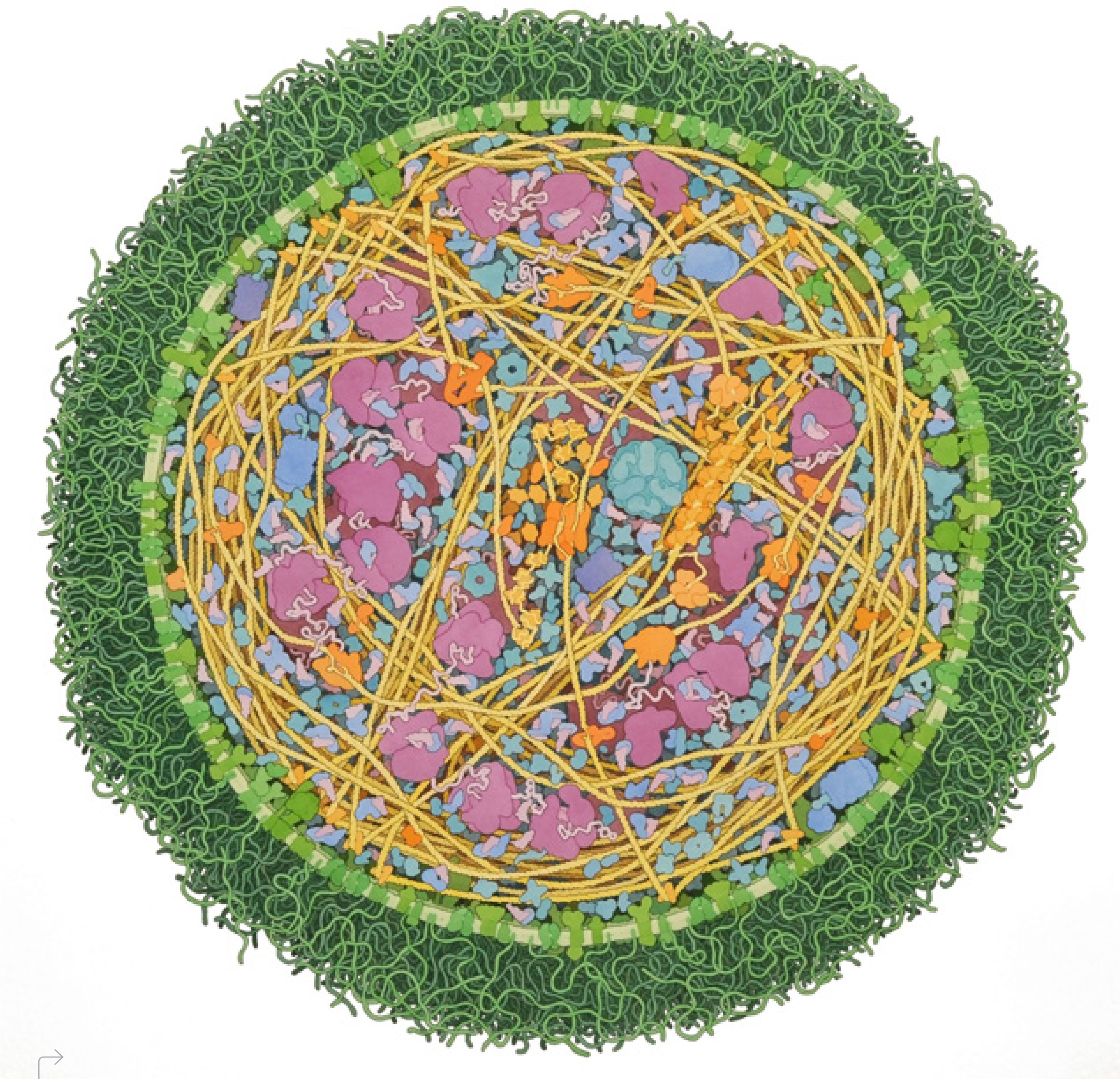
Nucleus: This view shows DNA being replicated in the nucleus. DNA polymerase is shown at the center in purple, with a DNA strand entering from the bottom and exiting as two strands towards the top. The new strands are shown in white. Chromatin fibers are shown at either site of the replication fork.

HIV in Blood Serum: This illustration shows HIV (the large spherical object in red) under attack by the immune system.

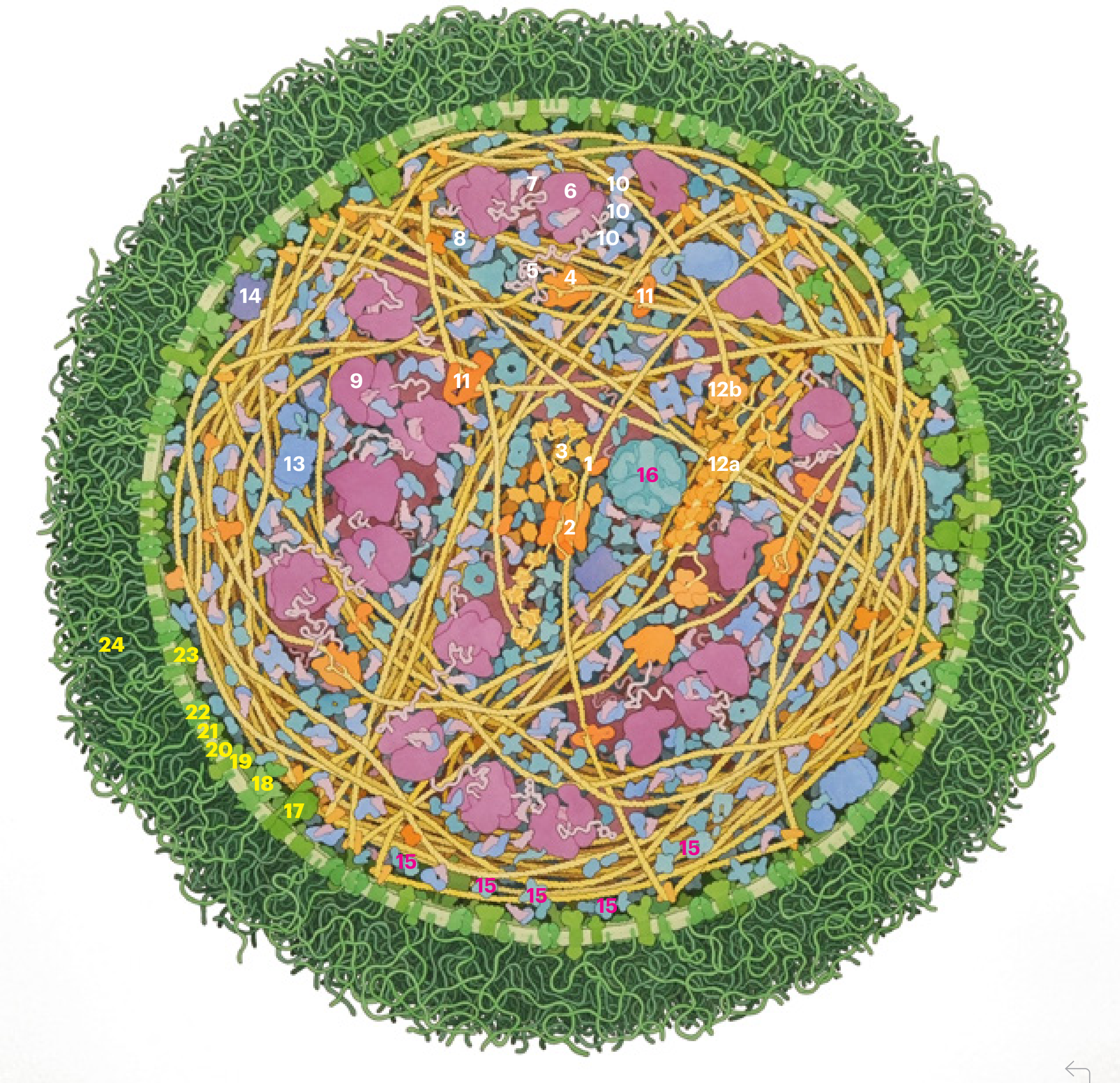


Small Y-shaped antibodies are binding to its surface.

Author:
David Goodsell



Mycoplasma mycoides: Mycoplasmas are some of the simplest cells on Earth. This painting shows a cross section through an entire cell, showing all of the macromolecules. Small molecules like ATP, glucose, and water are omitted for clarity.

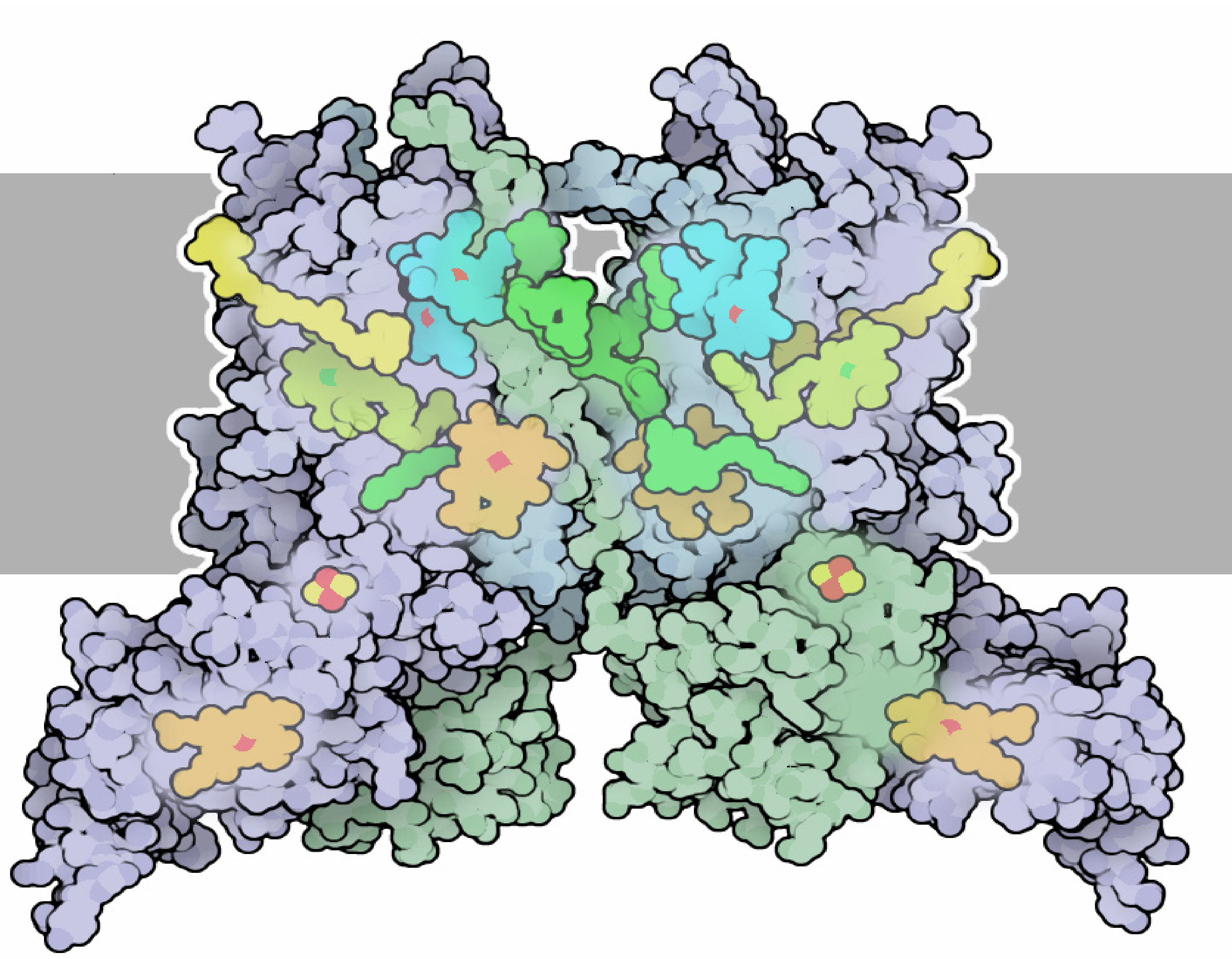


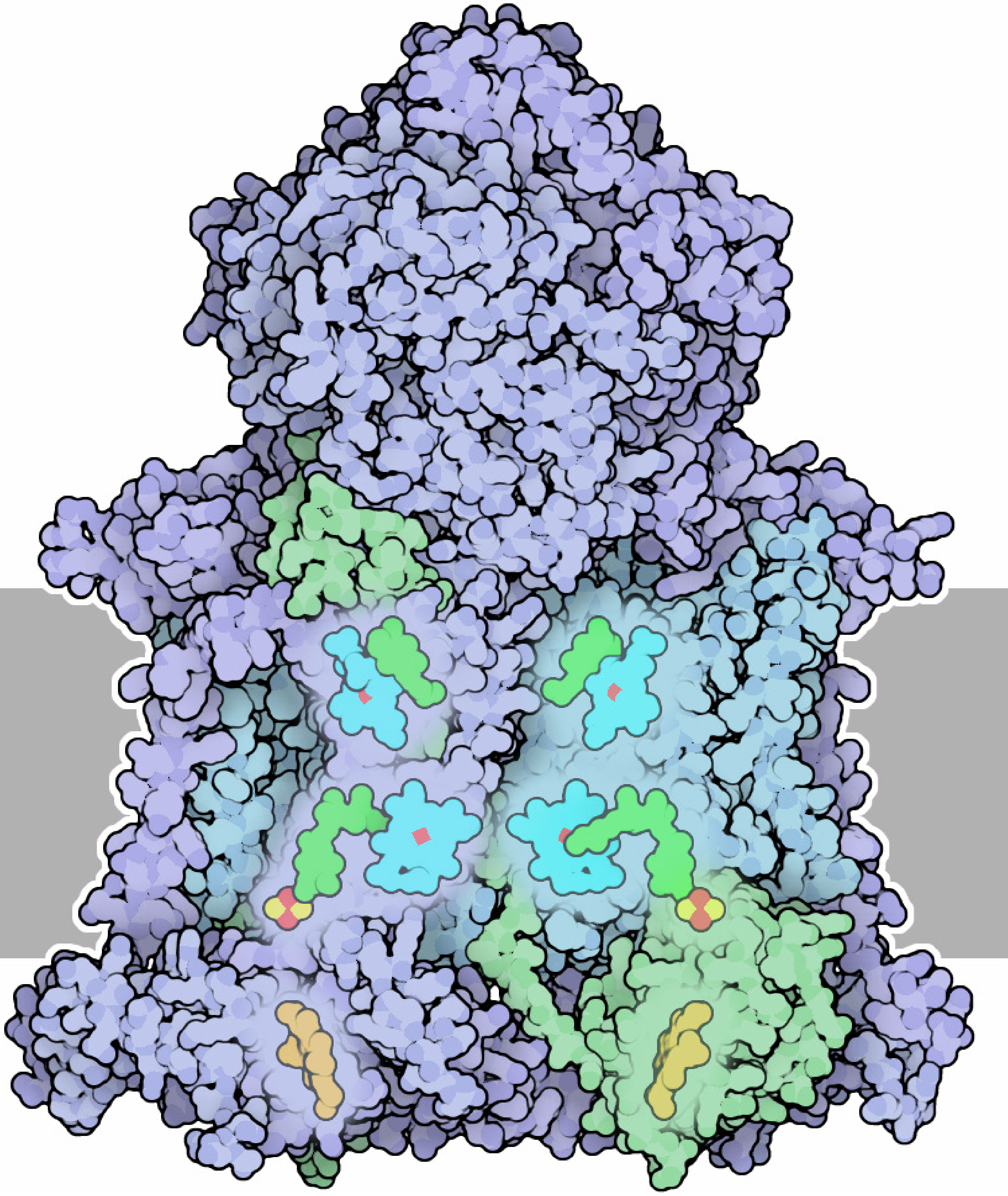
Protein synthesis (labels in white): 1. DNA, 2. DNA polymerase, 3. single-stranded-DNA binding protein (protects single-stranded portions during replication), 4. RNA polymerase, 5. Messenger RNA, 6. Ribosome, 7. Transfer RNA (in pink) and elongation factor Tu (in blue), 8. Elongation factor Tu and Ts, 9. Elongation factor G, 10. Aminoacyl-tRNA synthetases, 11. Topoisomerases, 12. Rec system for DNA repair: a) RecA, b) RecBC, 13. Chaperonin GroEL (helps folding of new proteins), 14. Proteasome ClpA (destroys old proteins) | Enzymes for energy production (labels in fuschia): 15. Glycolytic enymes, 16. Pyruvate dehydrogenase complex | Membrane proteins (labels in yellow): 17. ATP synthase, 18. Secretory proteins, 19. Sodium pump, 20. Zinc transporter, 21. Magnesium transporter, 22. ABC transporter, 23. Magnesium transporter, 24. Lipoglycan

summer 2012

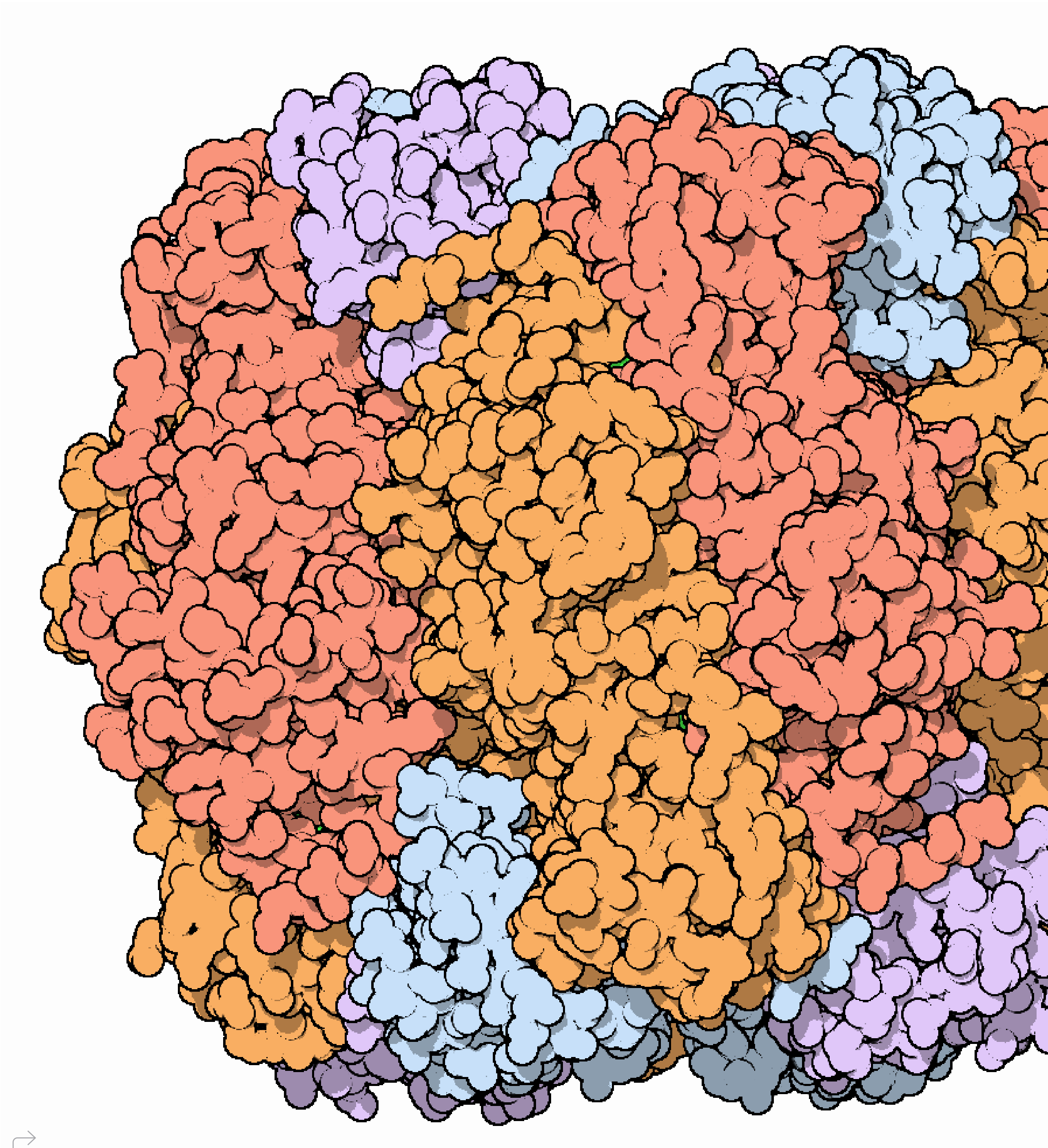
Portfolio

Author:
David Goodsell

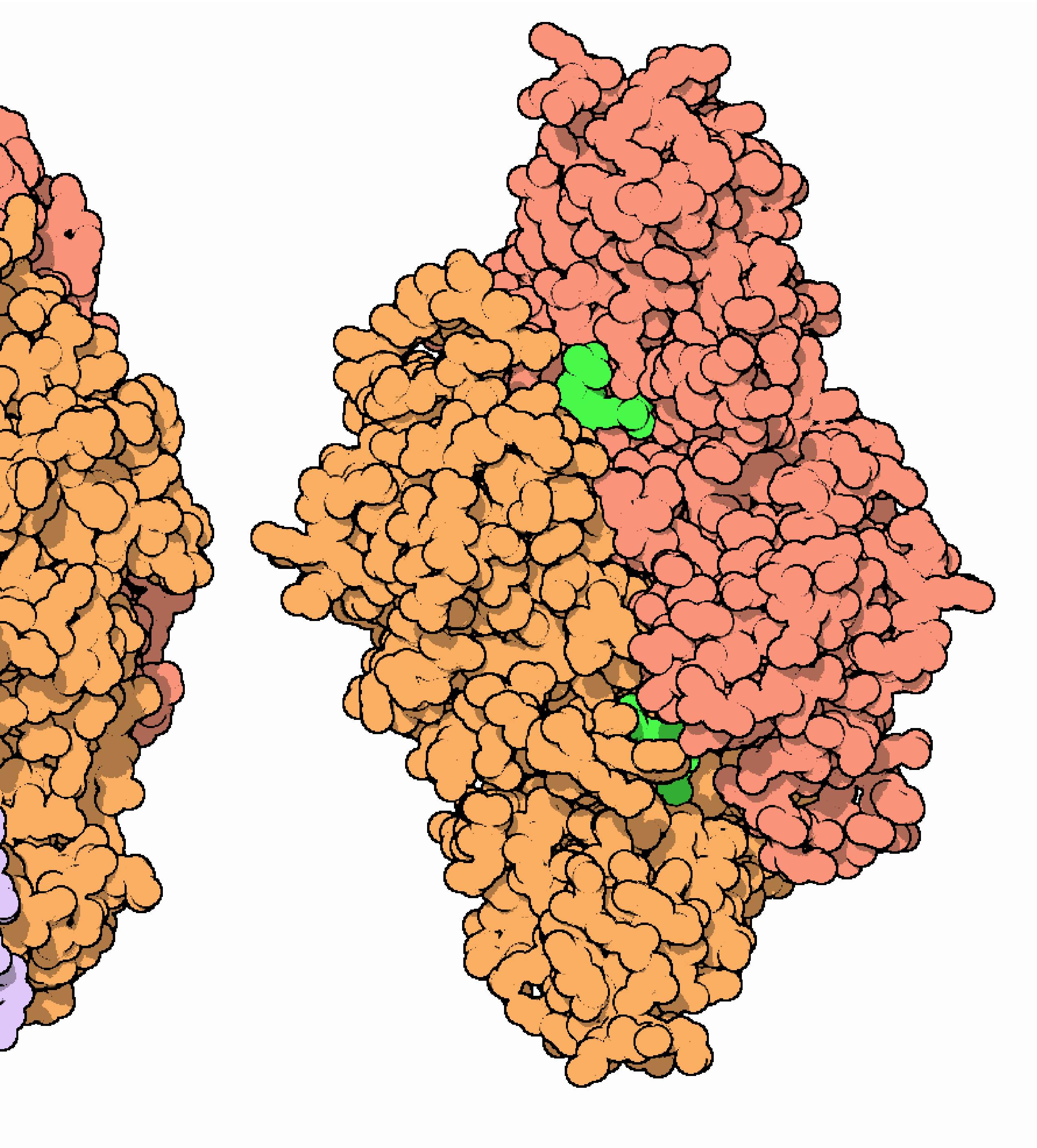


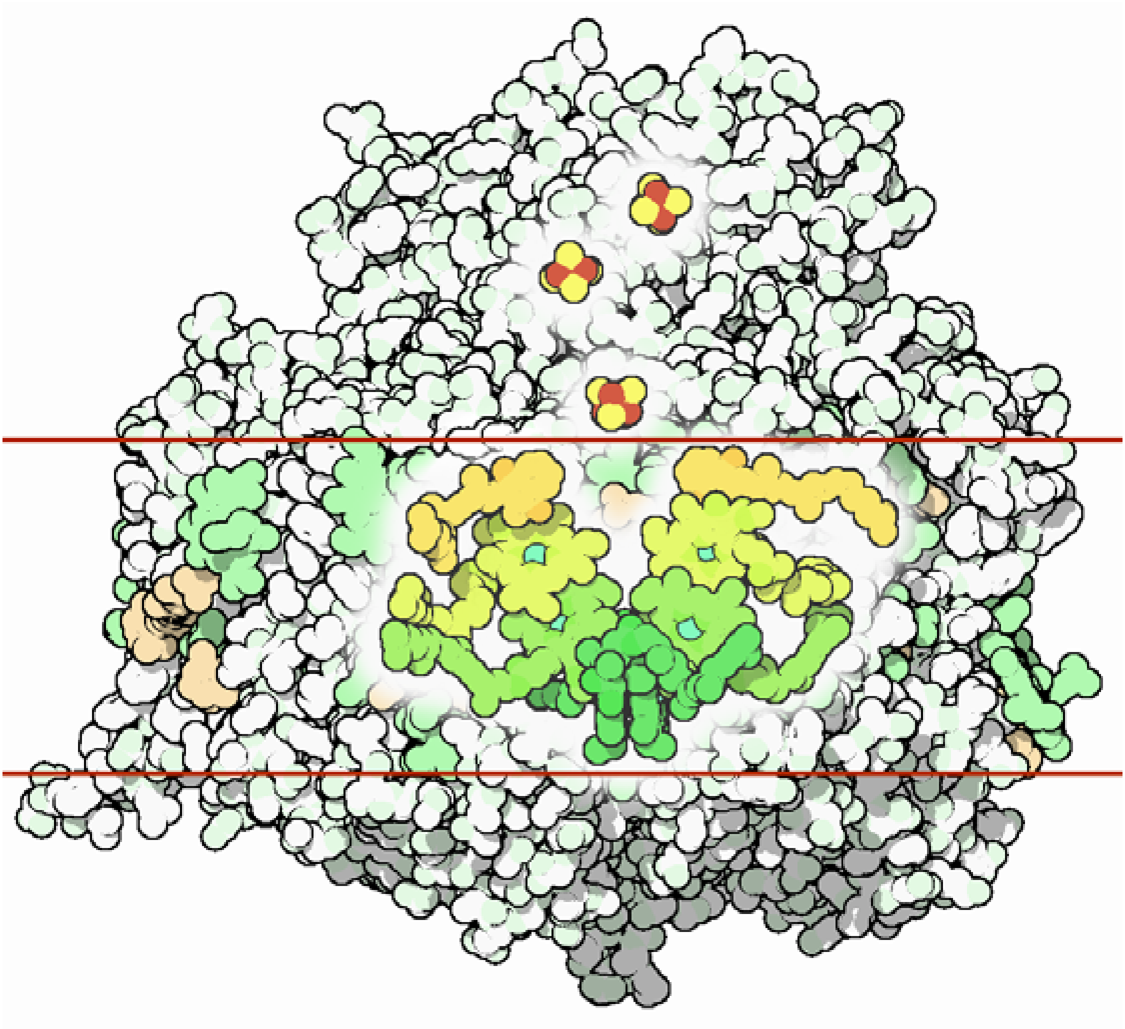


Photosynthesis | Cytochrome bc1: Proteins from Electron Transport Chains. These two proteins are proton pumps powered by a flow of electrons. Cytochrome b6f (left) is powered by electrons from photosynthesis and cytochrome bc1 is powered by electrons from food. The illustrations were created using atomic structures from PDB entries 1vf5 and 3h1j.

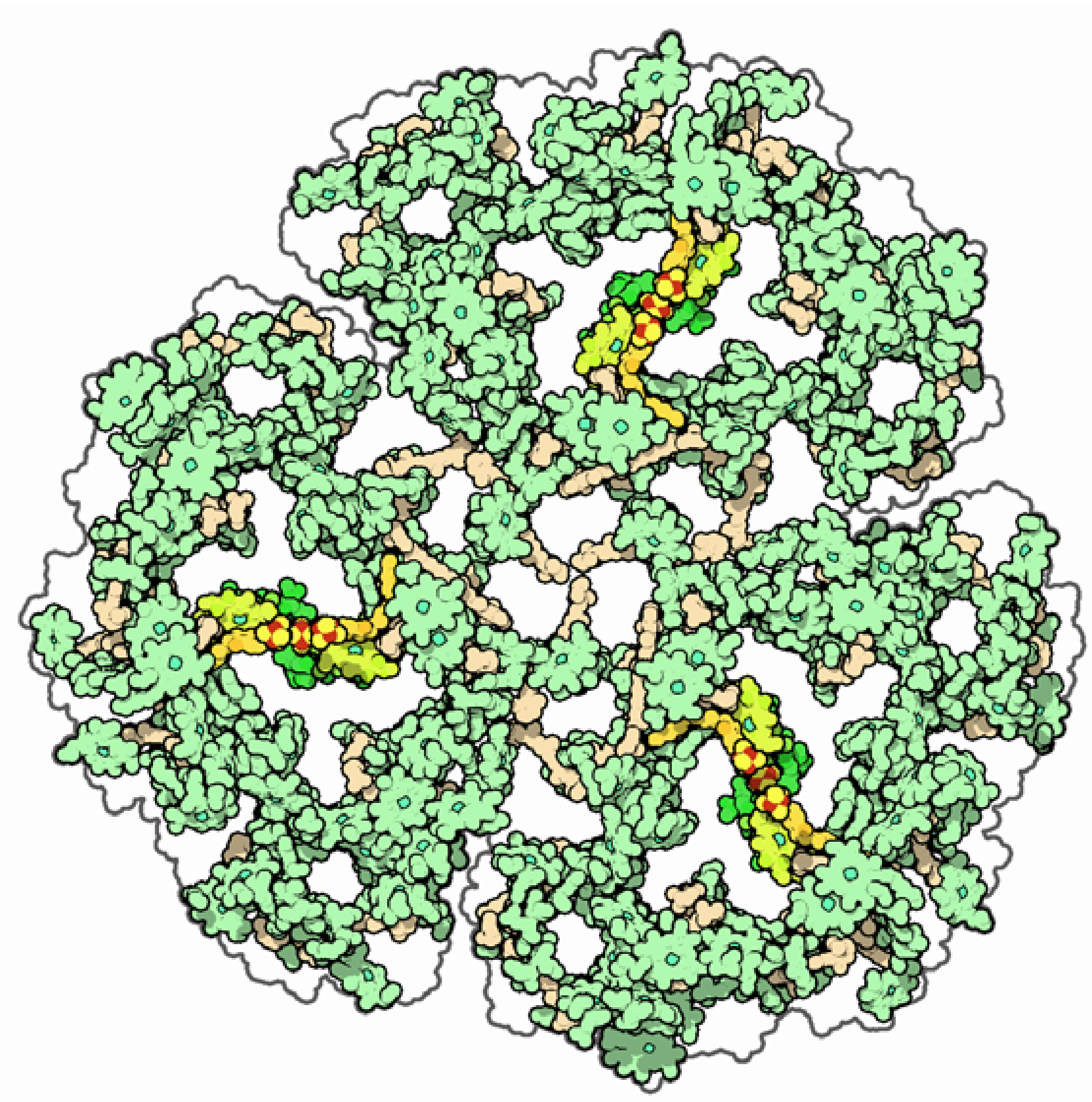


Photosynthesis | Rubisco: Rubisco is the most plentiful enzyme on Earth. It performs a central step in the fixing of carbon by photosynthesis. Two forms are shown here, one from spinach leaves (left, PDB entry 1rcx) and a smaller one from bacteria (right, PDB entry 9rub).

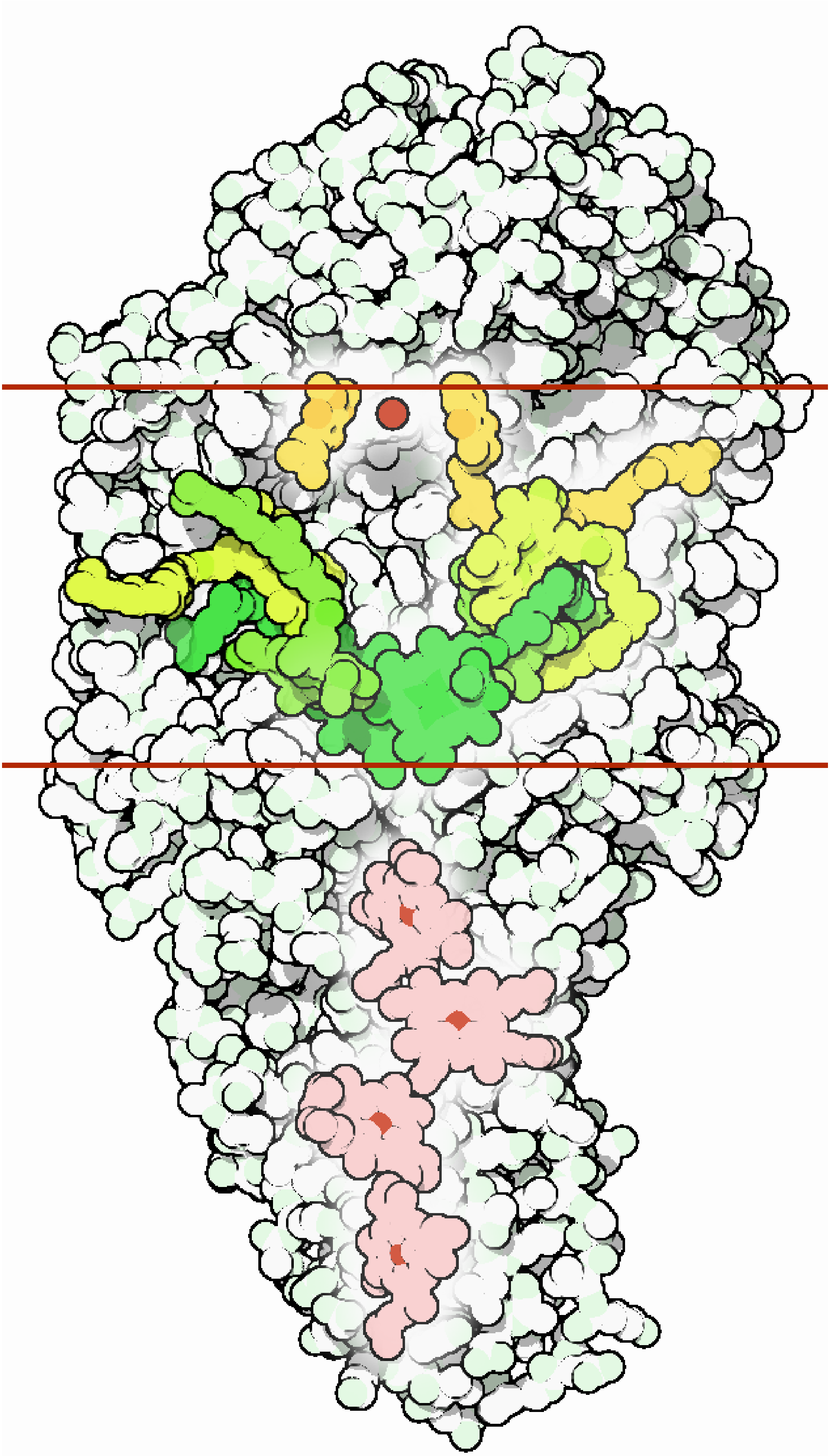


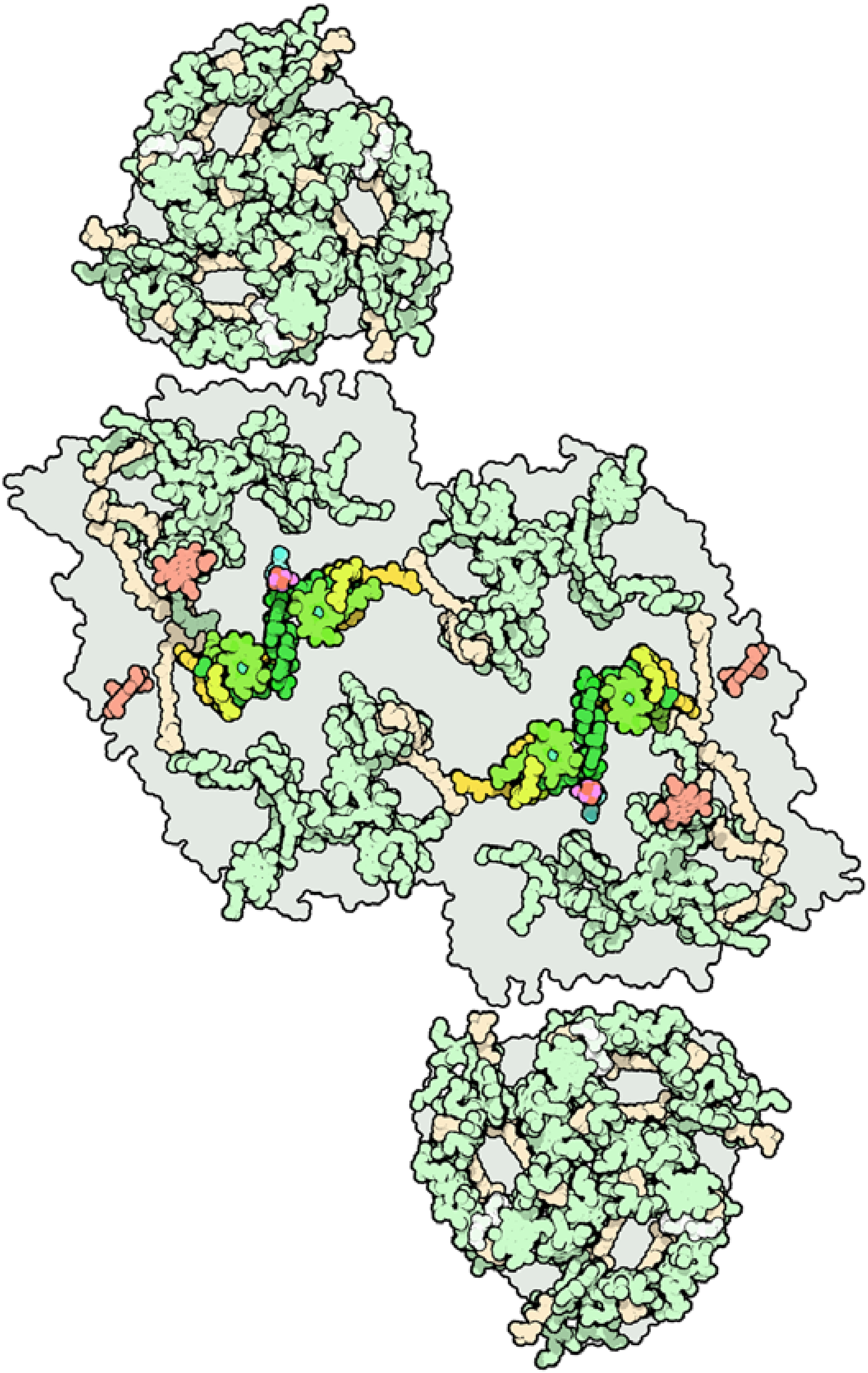


Pp 78-81. Photosystems: Plants, algae, and other photosynthetic organisms capture light using photosystems, which transform the light energy into a flow of high-energy electrons. Photosystem I from plants is shown on these two pages,



showing the many cofactors that gather light and control the flow of electrons. The following two pages include photosystem II, shown with two triangle-shaped light-harvesting proteins that help gather light, and a smaller photosynthetic reaction center made by bacteria. The illustrations were made using PDB entries 1jbo, 1s5l, 1rwt and 1prc.





Insect

Photo: -RobW-, 2009 | Flickr cc

Opinion

Biomimetics: Ten Assumptions I Question

Nikolay Bogatyrev

Author:
Nikolay Bogatyrev

Nikolay Bogatyrev is a TRIZ expert and consultant with more than 20 years of experience in the UK and Russia. He teaches TRIZ at the University of Bath for future engineers and managers. He started to use TRIZ himself being a PhD student at Novosibirsk State University and was fascinated by the power of this system: in a couple of years he sold 28 patents for a new lab research equipment.

Nikolay has a PhD in Biology, but is mostly interested in an engineering approach and ecologically sound architecture and design. He has more than 80 publications ranging from popular science papers to research articles and books. Applying TRIZ in ecology and agriculture Nikolay developed a set of rules for eco-engineering and published them in a book *Ecological Engineering of Survival*. From 2002 Nikolay has worked at the University of Bath (Mechanical Engineering Department).

He employs TRIZ in biomimetics as a tool for systematic transfer of mechanisms and effects from biology to technology.

Living nature is reliable, adaptable and sustainable. This has been proven by millions of years of evolution and is successfully applied today in the cutting-edge field of engineering, biomimetics.

Biomimetics is a relatively young branch of engineering methodology, but those who wish to trace its roots may find many historical attempts to copy nature. For example, Leonardo da Vinci observed animals and plants and foresaw the possibility of converting biological principles into technological ones. Later, more emphasis was placed on the need to increase the functional capability of engineering devices. Today, biomimetic ideas are also driven by the concepts of sustainability and nature-friendly engineering as we face the issue of the destruction of our planet's biosphere.

In recent years we have observed the growth in popularity of biomimetics. It has happened because of the wrenching changes which contemporary society faces now: ecological crisis, climate change, and health-threatening pollution of the environment. It has appeared that the conventional engineering approaches do not necessarily work as effectively and efficiently as we had expected. This is especially apparent if we take into account their global impact on our life. These issues have started to attract the attention of governments, media, architects, designers, engineers and the general public. No doubt science fiction books, films, Internet discussion forums, computer games, and other media have warmed the public's interest in copying nature and seem to have turned it into a kind of fashion.

Biomimetics takes ideas from biological systems and transfers them into technological implementation. Thus, the profession is in a mediatory position between biology and technology. There is clearly a need for cross-domain and cross-cultural knowledge transfer. Engineers and scientists in collaborative biomimetic projects face serious differences between their respective methodologies (scientists describe and model, while engineers prescribe and produce) and cultures (biologists study life, engineers design, build, and maintain machines).

Historically these two domains, biology and engineering, were very distant from each other, yet the biomimetic approach requires these two realms to be as close as possible. Ideally, they

Caffeine crystals

Photo: Annie Cavanagh, Wellcome images, 2012 | Flickr cc should both be present in the one head of the person who works on a biomimetic project. But this is not achieved easily, because it requires a large change in our education system. Biomimetic education is not so widespread as we might wish: there are few teachers who are professionally qualified in both biology and engineering.

Often those who teach tend to keep the discussion either within biology or engineering. Moreover, to get a profound education (do not confuse education with training!), rather than "intellectual fast-food", I believe that one should spend twice as much time and effort to become a professional engineer and a professional biologist. This is not so easy in the current atmosphere of budget cuts and shortened matriculations. I believe that is why we have so many people involved in biomimetic developments that are excellent engineers, but have a school-level knowledge in biology or are highly qualified biologists with only a superficial understanding of what biological information is needed to develop a technology.

Finally, there is a large section of the public that is quite interested in biomimetics, but is educated in neither engineering nor biology. This section of the public believes sincerely in the promises of science fiction, and well they might. Glossy pictures, lovely urban legends and nearly plausible myths garnish the pages of the popular science press. Many have nothing to do with either engineering or biology. Still, many people expect the proffered miracles of this novel trend in science and technology.

As a result of the aforementioned, biomimetics remains a purely empirical discipline. It has no scientific methodology of its own and, therefore, uses just "good old" trial-and-error methods and inspirations. The living prototypes for biomimetic design often are chosen accidently and very often their functions are misinterpreted. Biological "paragons" often are found after the engineering device has been developed and the idea of biomimetic design is used mostly for marketing and advertising purposes. This is not a bad practice, in my opinion, as long as it is not confused with science and engineering. The frequent result is that the analogy between bio- and techno-systems is superficial, trivial or does not help to solve the engineering challenge. It is, very often, due to the lack of education in biology.

So, let us consider some of these popular assumptions that are suggested widely as the basis for biomimetic research and development. Let us see if they are solid enough to play the role of scientific or methodological guides for biomimetic design:

1. "Biomimetics is about copying and imitating nature".

   We might discuss and dispute how to copy or what to imitate, but it would be besides the point, because direct and exact copying would be pointless, expensive, inefficient and possibly dangerous. Here is why I think so;

   A copy is always worse than the original. Having an original object, why would we need its copy, which is always worse by definition?

   We do not really need the complete copy – If we are going to produce an artificial biomimetic tooth, do we need caries and toothache also?

Rose Petal

Photo: Annie Cavanagh, Wellcome images, 2012 | Flickr cc

Life is poly-functional and is adapted to perform all of the functions, not just the one we need to copy. We do not need our vacuum cleaners to defend their territory or migrate every winter to the warmer climates.

2. " Life is always perfect". Another popular assumption: "Nature is always wise".

Not always and not everywhere. Mind the millions of extinct species in the course of the history of our planet and those that are dying out now. Some of them were doomed due to morphology, others to behavioral peculiarities, still others due to physiological reasons. If you think about the imperfections of the human body you will realize that natural "paragons" are not so common. "Nobody is perfect!" is, therefore, a very apt phrase. The whole reason for the origin and development of technology itself (tools, transport, agriculture, medicine, etc.) is, I believe, to compensate for the deficiency of our embodiment of living Nature. By the way, technology is not the unique feature of humans; many animals also compensate for their weaknesses by building nests, burrows, shelters, accumulating food for themselves or their off-springs, and by using various objects as tools for their every-day needs.

3. "Living nature uses only the energy it needs."

Most organisms, however, accumulate and deposit excessive amounts of food and/or structural substances. Often rodents cannot consume all the accumulated food of their grain storages. Squirrels hide their food (nuts, seeds, cones, etc) and often just forget these places with the hidden food. Honeybee-keeping would be impossible, if bees accumulated only the exactly required amount of honey for their own needs. If we consider the ecosystem level of living systems, we can cite the example of a pond that is gradually silted with the excessive organic matter, which cannot be processed by the organisms inhabiting the pond.

4. "Living nature recycles everything."

If this is so, why do we see surpluses so enormous that they cannot be processed, consumed, or digested and have to be deposited as coal, turf, oil, or limestone? One can say that those deposits will also be recycled eventually, but this will happen in the geological (not biological) time-scale and mechanisms whereas we are considering living systems and the time-scale that corresponds with a human life – tens and hundreds of years, but not millions and billions.

5. "Living nature rewards cooperation".

I would urge the reader to remember the competition, parasitism, cannibalism, commensalism and ammensalism that exist alongside mutualism (symbiosis) and can even easily transit from one relationship to another. For example, lichen is the symbiosis of a fungus and an algae. When environmental conditions have deteriorated the fungus will digest the algae, thus transitioning from mutualism to cannibalism.

6. "Life relies on diversity".

Northern ecosystems exist at a very low level of diversity, as do some grassland ecosystems. In Africa we see a great diversity of species of savannah antelopes, but in the similar environment of the North American prairie the same herbivorous function is performed by just one single species, the bison.

While living prototypes are extremely complex, we need, typically, minimum complexity, maximum simplicity and reliability, ease of operation and predictability. Such features are not easy to guarantee in the case of copying the biological prototype.

Lavender leaf

Photo: Annie Cavanagh, Wellcome images, 2012 | Flickr cc

7. “Living Nature runs on the energy of the Sun/sunlight.”

This is largely indisputable, but I would also point out that Chaemobacteria run on the energy of chemical substances deep in the soil or ocean. So biomimetic systems seem to use any energy or every opportunity to extract energy from any available source or process.

8 “Biomimetics will provide sustainability.”

This is not necessarily true, in my opinion. A natural tree is sustainable in the context of the forest ecosystem. If we make an artificial “timber” mimicking the structure of natural fibers and their spatial arrangement and that material is made of carbon fibers and epoxy resin, it will be the perfect biomimetic product, but the manufacturing process and the after-use recycling will be far from sustainable.

9. “Living nature fits form to function.”

This is true sometimes, I believe, but not universally. Very often the same function is provided with sufficiently different forms. Remember the shapes of fast-swimmers, whales and dolphins: the same effect is achieved with radically different shapes of the anterior part of the animals. Other cases could be even harder to approve: female hyenas give birth to their off-spring through a unique structure, an extremely narrow passage that passes through the clitoris. It is an amazing example of the total discoordination of sizes, forms and functions.

10. “Living nature optimizes rather than maximizes.”

This depends, I believe, on what kind of biological system we consider. The number of baby-elephants is always one and the number of eggs that spawn fish can number in the six digits. The amount of spermatozoa, the number of pollen grains and seeds, the sizes of mammoth’s tusks, the mass of dinosaurs appear, also, to be beyond the optimal. So, living nature seems to do it all: optimize, minimize and maximize , according to the given circumstances and available means.

Let me be clear: I am fully aware that all the principles listed above exist in nature, but, at the same time, the opposite statements are also true and similarly common in life. These principles represent just a smallest facet of the diverse strategies that Life as a phenomenon does possess.

There is one main feature of living nature that is omitted from this list: Life can possess totally and radically different features: it can be effective and inefficient, large and small, smart and stupid, slow and fast, adaptive and conservative... The professional biologist could easily fill the “space” of the continuum between these extremes with the full range of intermediary examples. This list would be very long indeed. This amazing multi-strategism of Life as a phenomenon is the feature that has allowed it to survive for billions of years in spite of all the changes and catastrophes in the history of our planet. ×

From Square Nature

Photo: m4tik, 2011 | Flickr cc

Tools

The Engineering to Biology Thesaurus

Jacquelyn Nagel

summer 2012

Tools:
The Engineering to Biology Thesaurus

Author:
Jacquelyn Nagel

What is your tool?

Jacquelyn: The Engineering-to-Biology (E2B) Thesaurus is a design tool that lowers the hurdle to working across professional domains, allowing engineers without advanced biological knowledge to leverage nature's ingenuity during engineering design [1, 2]. Biological terms in the thesaurus are correlated to the engineering domain through pairing with a synonymous function or flow term of the Functional Basis, an engineering modeling lexicon. Biological terms are mapped to an engineering modeling lexicon that frames the biological information in a context familiar to engineers.

Why is your tool needed?

Jacquelyn: Although many biologically-inspired solutions are innovative and useful, the majority of inspiration taken from nature has happened by chance observation, by dedicated study of a specific biological entity such as the gecko, or by consulting a biologist. This reveals a fundamental problem of working across the engineering and biological domains. Engineers may encounter several challenges when performing biomimicry, which include:

- Terminology differences
- Understanding how a biological system works or functions
- Discovering relevant biological solutions
- Abstracting biological principles/solutions for inspiration

The effort and time required to become a competent engineering designer leaves little opportunity to learn about biological systems (the converse can also be said). My aim is to remove the element of chance, reduce the amount of time and effort required to develop biologically-inspired solutions, and bridge the seemingly immense gap between the engineering and biological domains. I hope to do this through the development of design tools. One specific tool that attempts to address these challenges is the Engineering-to-Biology (E2B) Thesaurus [1, 2], graphically depicted in Figure 1.

The three key goals of the E2B thesaurus are to (1) lessen the burden when working with knowledge from the biological domain by providing a link between engineering and biological terminology; (2) assist designers with establishing connections between the two domains; and (3) to facilitate bioinspired design during many steps of the engineering design process.

Who is your tool for?

Jacquelyn: The E2B thesaurus is specifically for engineers who wish to design using information and principles from the biological domain, but, I think, could be useful for other designers.

What phase of development is your tool in?

Jacquelyn: The tool is a work-in-progress and could be considered a late stage alpha prototype. Usage is still a manual process, but the tool has proven to enhance the concept generation process in many ways [1, 9, 10].

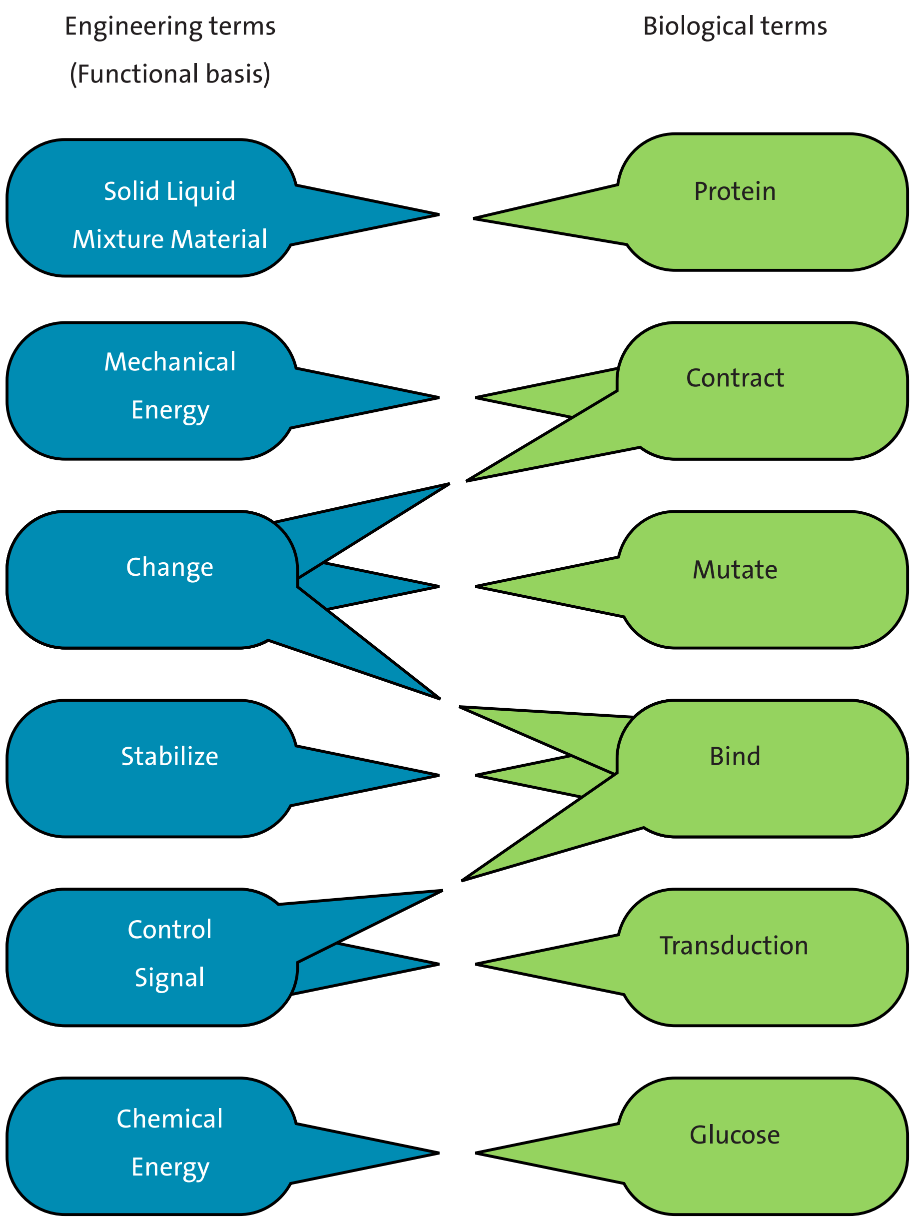


Figure 1: Graphic representation of the engineering-to-biology thesaurus

Next steps include implementing the thesaurus as a database and expanding the terms included. A designer could explore the database and identify associations between the domains as well as allow for other information to be linked to the terms. Digital implementation would also allow integration with computational design tools. I expect that expanding the included terminology will make the tool more useful to both novice or expert designers.

How could it be used?

Jacquelyn: Applications of the E2B Thesaurus include, but are not limited to, (1) translation of biological information to increase comprehension, (2) identification of relevant biological terms to use during brainstorming or searching for biological inspiration, (3) functional modeling of biological systems, (4) identification of analogies between the domains, and (5) dialogue facilitation between the engineering and biology communities. All these design activities lead to concept development, which is an overarching application of this design tool. An additional point is that many of these applications capture the biological system through an abstraction, which is very valuable in solving design problems and can assist designers with learning design principles from nature.

What is your conceptual approach?

Jacquelyn: As its name suggests, my approach to interfacing biological information with engineering design is through terminology, specifically through grouping synonyms and related concepts in a classified form as a thesaurus. Linking biology terms to engineering modeling terms (used for functional representation and abstraction) assists with re-framing the biological terminology in an engineering context. Thus, the biological information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methodologies.

The E2B Thesaurus does not include every engineering and biology term; rather, it contains a representative set of engineering and biology terms. The engineering terms comprise the Functional Basis modeling lexicon [3] that has both function (action being carried out on a flow) and flow (type of energy, signal and material that travels through a device) terms. To map terminology between domains, the representative set of biology terms are grouped with engineering terms according to the classification of the Functional Basis.

The E2B Thesaurus, however, does more than arrange terminology of one domain side-by-side with terminology of another; it serves as the intermediary between the biology and engineering domains. Furthermore, this design tool increases the interaction between the users and the knowledge resource [4] and aims to increase a designer‘s efficiency when working across the engineering and biology domains.

How does one use it?

Jacquelyn: The E2B Thesaurus can be accessed via the Design Engineering Lab website. Since the tool is still in manual form the links below take you to PDF versions of the thesaurus tables. The tool has two available formats: 1) sorted by

From Square Nature

Photo: m4tik, 2011 | Flickr cc

Sunrise in Dew Drops on Spider Web

Photo: Photomatt28, 2006 | Flickr cc

engineering flow and function, and 2) sorted alphabetically by biological term. Both versions are searchable PDFs. The following link provides access to the tables sorted by engineering flow and function:

http://designengineeringlab.org/delabsite/publications/conferences/E2B_thesaurus.pdf

The following link provides access to the tables sorted alphabetically by biological term:

http://designengineeringlab.org/delabsite/publications/conferences/E2B_Thesaurus_v2.pdf

The two versions assist a designer in different ways. "Looking for biological terms that correlate to engineering terms", the first format, assists mainly with identification of relevant biological terms to use during brainstorming or searching for biological inspiration. It also supports identification of analogies between the domains, and dialogue facilitation. "Looking for engineering terms that correlate to biological terms", the second format, assists mainly with translation of biological information, but also supports functional modeling of biological systems, identification of analogies between the domains, and dialogue facilitation. Examples of using both formats are given below.

Finding relevant and inspiring biological systems can be a challenge when addressing an engineering problem. The biological terms of the Engineering-to-Biology Thesaurus can be useful because they offer more functions for brainstorming and relevant keywords to consider. A general approach to identification of relevant biological systems for design inspiration would proceed as follows:

- Define the engineering problem or need.
- Mark or define engineering function or flow terms that are associated with the problem or need.
- Look up the engineering terms in the E2B Thesaurus table sorted by engineering flow and function.
- Use the corresponding biological terms to brainstorm or search for biological systems that perform the function or include the flow. Reliable resources for searching are:
- The Bio Search Tool – A web-based tool that searches an introductory level biology textbook for the specified search terms.
- Design Repository – A database of product design and biological system knowledge indexed by engineering function and flow.
- Ask Nature – An online inspiration source for the biomimicry community.

http://www.asknature.org

- Designer Note: I search all the biological terms associated with each engineering function and flow term to have the greatest number of inspiration sources.
- Use all or a narrowed list of identified relevant biological systems for design activities.

An example of applying the E2B Thesaurus is with identifying biological systems to use for design inspiration. Consider the design of a braking system for a pedaled vehicle, such as a bicycle. In order to define the functions and flows associated with the design problem the

Social Network

Photo: aspheric.lens, 2008 | Flickr cc

designer needs to answer: What is the core function of "braking"?, or What purpose does "braking" serve?. Another way to describe braking in engineering terms is stopping or simply stop. Looking for the engineering term stop in to the E2B Thesaurus leads to the biological terms of extinguish, halt, clog, seal and suspend. This set of biological terms provides a wide range of terms to assist with brainstorming or searching to identify biological systems that address the design problem. With the expanded set of functions, the designer needs to answer What biological systems extinguish?, or What in nature extinguishes?. Answering these questions for each biological term leads to a set of biological systems that can be used for addressing the design problem. Identified biological systems using brainstorming, pulling from my own knowledge of biology, are fainting goats, spider webs, puffer fish, and giraffe throat valves. Identified biological systems using the search techniques include: clam shells, blood clots, and scabs. Next, I would use the identified biological systems for design inspiration or other design activities, if I fully understood them.

If I did not fully comprehend the biological systems I would translate the information into an engineering context. A typical challenge for an engineer without biology training is reading biological literature. Translation of the unfamiliar biological terminology into an engineering context aids with comprehension. If an interesting biological system has been identified, a general approach to direct translation of biological information into an engineering context would proceed as follows:

- Read about and analyze the biological system.
- Mark biological terms that make the information difficult to understand.
- Look up the biological terms in the E2B Thesaurus table sorted alphabetically by biological term.
- Read the corresponding engineering terms. Choose an engineering term to replace the biological term.
- Replace the marked biological terms with the corresponding engineering terms.
- Read over the translated text. Translate more or fewer terms as necessary until comprehension is achieved. *Designer Note: I try to also create a summary of the translated text using engineering terms. This supports archival of the translated information and communication with other designers.
- Use translated information for design activities.

An example of direct translation following the steps outlined above is given. Consider the biological phenomenon of abscission described in the following excerpt:

> 'Leaf fall (abscission) is regulated by an interplay of the hormones ethylene and auxin. The effect of auxin on the detachment of old leaves from stems is quite different from root initiation. This process, called abscission, is the cause of autumn leaf fall. Leaves consist of a blade and a petiole that attaches the blade to the stem. Abscission results from the breakdown of a specific part of the petiole, the abscission zone. ... The time of abscission of leaves in nature appears to

Spider web

Photo: luc.viatour, 2007 | Flickr cc

> be determined in part by a decrease in the movement of auxin, produced in the blade, through the petiole.' – [5]

Depending on the background knowledge of the designer, several biological terms could be chosen for translation. To change the context of the excerpt, the terms abscission, hormone and auxin are chosen. Applying direct translation the excerpt now reads as follows:

> Leaf fall (separation) is regulated by an interplay of the liquid-liquid mixture materials. The effect of liquid-liquid mixture material on the separation? of old leaves from stems is quite different from root initiation. This process, called separation is the cause of autumn leaf fall. Leaves consist of a blade and a petiole that attaches the blade to the stem. Separation results from the breakdown of a specific part of the petiole, the separation zone. ... The time of separation of leaves in nature appears to be determined in part by a decrease in the movement of liquid-liquid mixture material, produced in the blade, through the petiole.

From this translation a designer could summarize abscission as: When a liquid material stops flowing between the plant and the leaves, a separation zone occurs and the leaf separates from the plant. Next the designer would use the translated information for design inspiration, and, then, identify or design engineered components that could be used to replicate the engineered system derived from the natural system.

In addition to the inspiration, brainstorming, search and translation functions, other practical benefits of the E2B Thesaurus include: functional modeling, analogy formation, concept generation, and encouragement of interdisciplinary dialogue.

Where will you go from here?

Jacquelyn: The E2B is envisioned as a design tool that will enable or enhance collaboration between biologists and engineers. The Engineering-to-Biology Thesaurus encourages the discovery and creation of biologically-inspired engineering solutions through the engineering design applications discussed in this article. Once conceptual designs have been created the next step is to create proof-of-concept prototypes or models to determine the feasibility of the biologically-inspired design. Designers can obtain more background information and details on the Engineering-to-Biology Thesaurus from [1,2,11,12].×

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References

1. Nagel, J.K.S., Stone, R.B., McAdams, D.A. (2010) "An Engineering-to-Biology Thesaurus for Engineering Design." *ASME IDETC/CIE 2010 DTM-28233*, Montreal, Quebec, Canada.

2. Stroble, J.K., Stone, R.B., McAdams, D.A., Watkins, S.E. (2009) "An Engineering-to-Biology Thesaurus to Promote Collaboration, Creativity and Discovery." *Proceedings of the CIRP Design Conference 2009*, pp. 335-368, Cranfield, Bedfordshire, England.

3. Hirtz, J., R. Stone, D. McAdams, S. Szykman & K. Wood (2002). A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. *Research in Engineering Design*, *Vol.*13, No.2, 65-82

4. Lopez-Huertas, M.J., 1997, "Thesaurus Structure Design: A Conceptual Approach for Improved Interaction," *Journal of Documentation*, *53*(2), pp. 139-177.

5. Purves, W.K., Sadava, D., Orians, G.H. and Heller, H.C. (2001) *Life, The Science of Biology*, 6 ed., Sunderland, MA, Sinauer Associates.

6. Stroble, J.K., Stone, R.B., McAdams, D.A., Goeke, M.S., Watkins, S.E. (2009) "Automated Retrieval of Biological Solutions to Engineering Problems." *Proceedings of the CIRP Design Conference 2009*, pp. 78-85, Cranfield, Bedfordshire, England.

7. Nagel, J.K.S., Stone, R.B., McAdams, D.A. (2010) "Function-Based Biology Inspired Concept Generation." Chapter 5 in *Biomimetics, Learning From Nature*, pp. 93-116, In-tech, Croatia. ISNB:978-953-307-025-4

8. Nagel, J.K.S., Stone, R.B., McAdams, D.A. (2010) "Exploring the Use of Category and Scale to Scope a Biological Functional Model." *ASME IDETC/CIE 2010, DTM-28873*, Montreal, Quebec, Canada.

9. Nagel, J.K.S., Nagel, R.L., Stone, R.B., McAdams, D.A. (2010) "Function-Based, Biologically-Inspired Concept Generation." Artificial Intelligence for Engineering Design, Analysis and Manufacturing, special issue *Biologically Inspired Design*, *Vol*. 24(4) pp. 521-535.

10. Nagel, J.K.S., Stone, R.B., 2012, "A Computational Approach to Biologically-inspired Design," Accepted on November 16, 2011 to *AIEDAM special issue DCC 2010*. To be published in Spring 2012, Vol. 26, No.2.

11. Nagel, J.K.S., Stone, R.B. (2011) "A Systematic Approach to Biologically-inspired Engineering Design." *ASME IDETC/CIE 2011, DTM-47398*, Washington, D.C., USA.

12. Nagel, J.K.S., "A Thesaurus for Bioinspired Engineering Design." Chapter in *Biologically Inspired Design: Computational Methods and Tools*, A. Goel, D.A. McAdams, R.B. Stone (eds.), Springer. Spring 2013.

Tensegrity

Photo: beckstei, 2012 | Flickr cc

Two Perspectives

Bucky and the Shape of Nature

Curt McNamara

Bucky and the Shape of Nature

Bucky

R. Buckminster Fuller was one of the earliest designers of sustainable solutions, inventing high efficiency cars, low flow showerheads, and efficient housing in the 1930's. He was also part of a long line of thinkers who recognized the beauty of nature's design, and the comparably lesser results in the designs of Man (1).

His lifelong search was for the underlying geometry of nature. The results of his work were published in the two-volume set, *Synergetics I* and *II*. In the 1990's, Robert W. Gray transferred both volumes to a web site and published a comprehensive index to the material (2). The volumes contain information on the nature of systems, the fundamental shape of space, and universal principles that Bucky believed governed all design.

It can be daunting to explore this material because of Fuller's precise use of language and his depth of discourse. In this article I will explore some topics from *Synergetics* that have been used to describe natural systems, and to create highly efficient human-made structure.

Fullers' main quests were to find:

- The basis for minimal structure
- Deep principles of design with nature
- The coordinate system used to combine material in nature

The answers he found were:

- Tensegrity (coupled tension and compression) is the basis for minimal structure.
- Geodesics are an expression of tensegrity. They can be used to cover space efficiently, and to describe the organization of substances such as C60 (buckminsterfullerene).
- There is a structure that can fill all space starting from a single point and linking to other points. It is known by many names: 12 spheres around 1; the cuboctahedron with an internal point; the Isotropic Vector Matrix (IVM); the face centered cubic crystal system.
- Science consists of generalized principles (relations) that exist between elements and not in the elements themselves. An example is gravity. All science and structure is a search for the most elegant relations.

My article will look at how these ideas have been applied in design and biology, and I will suggest what further work can be done.

Biomimicry

Common practices of biomimicry seem to range from surfaces to structures to system (3), or from function or form to process to system (4). Entities and systems exist at each level, structured

Untitled (geodesic in nature)

Photo: Lon Fong, 2010 | Flickr cc

Tetra Classic: 1950s

Photo: Tetra Pak, 2010 | Flickr cc

according to universal principles. At each level these entities and systems couple or contact one another.

While it may seem that each of these domains is distinct and requires a separate set of skills to navigate, Buckminster Fuller did not find this to be true. Rather, he clarified and made visible the basics of the shape of space from the microscopic to the macroscopic. It is worth noting that even process can be seen as a change in geometry, shape, or connections over time.

What are the principles he found, and how can these be used in biomimicry?

The Shape of Nature

To start the process he looked for the simplest system or structure. The minimum shape that encloses space is a tetrahedron, which consists of four points. Two points define a line, three points a plane or a triangle, and four points encloses space. Therefore four points define the minimum system. This is a fundamental of synergetics: all systems enclose space.

If there are less than four nodes or corners, it is not a system. This seems puzzling as there are systems described by words or equations that may not seem to enclose space. However, a careful examination will reveal that there are four or more coupled nodes in all complete system descriptions. Even our thoughts exist in physical space (mapped across neurons).

Thinking of the tetrahedron as a set of four points brings us to another fundamental: all shape is a result of coupled forces. The tetrahedron we are describing is not four sides nor is it a solid block. It is four nodes coupled by six relations. The nodes are the corners of the tetrahedron where the coupled forces come together. What are the coupled forces? Fuller refers to these as relations; each relation is an example of a universal principle.

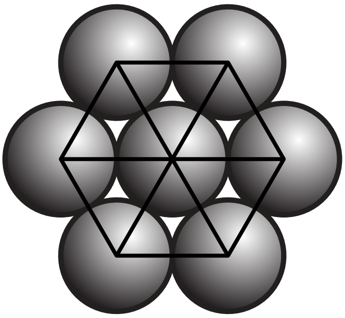
An example is the force of gravity. If the nodes are particles of material, or planet and moon, the relation that is gravity exists between them and not in each one. Similarly, the electromotive force exists between and not in the fundamental charges. It is possible to go through the catalog of forces and confirm that each one holds true to this observation.

In the creativity tool TRIZ the progression of forces are known as MATCHEM: mechanical (friction); acoustic (waves); thermal (Brownian motion); chemical (bonding); electric (potential and flow); and magnetic (wave). Each force or field is a relation that exists between and not in the parts.

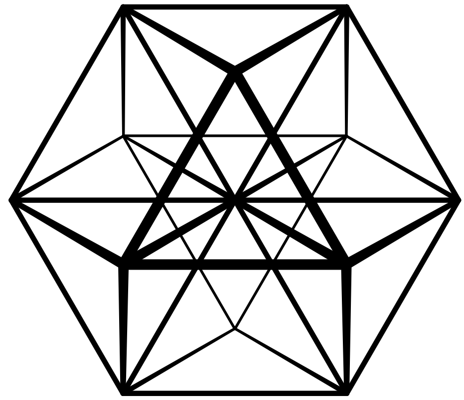
The relations can be depicted as vectors pointing in the direction of the field. A vector exhibits magnitude and direction to illustrate the fields' properties. A line can be used to indicate the presence of a vector, or a track to show where the vector was. It is important to note that in Synergetics the vectors, relations, lines and fields do not meet or cross at the corner of the structure. Rather the corner represents the interaction that creates the structure.

Relations and corners

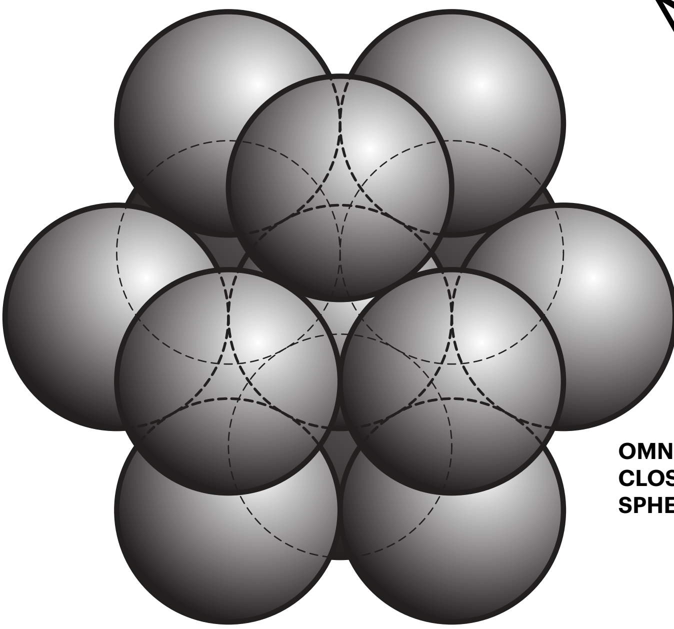
In Synergetics, Nature only allows a small number of connections at a node: three in the case of the



CLOSEST-PACKED SPHERES IN THE PLANE



Vector Equilibrium



OMNI DIRECTIONAL CLOSEST-PACKED SPHERES

Vector Equilibrium: Omnidirectional Closest Packing Around a Nucleus: Triangles can be subdivided into greater and greater numbers of similar units. The number of modular subdivisions along any edge can be referred to as the frequency of a given triangle. In triangular grid each vertex may be expanded to become a circle or sphere showing the inherent relationship between closest packed spheres and triangulation. The frequency of triangular arrays of spheres in the plane is determined by counting the number of intervals rather than the number of spheres on a given edge. In the case of concentric packings or spheres around a nucleus the frequency of a given system can either be the edge subdivision or the number of concentric shells or layers. Concentric packings in the plane give rise to hexagonal arrays and omnidirectional closest packing of equal spheres around a nucleus gives rise to the vector equilibrium.

Text source: http://www.rwgrayprojects.com/synergetics/s04/figs | Graphic: Colin McDonald tetrahedron; four in the case of the octahedron; and five in the case of the icosahedron. More complex structures are combinations of these.

Boundary

The surface of a system is a boundary. The boundary separates the system (inside) from the world (outside). The boundary elements are tightly bonded to each other, and may have different characteristics for the interior vs. the exterior. Many biomimicry applications are at the boundary layer and are related to how one system contacts another.

Fuller believed that a boundary is a mesh of nodes, each coupled to between three and five other elements. The nodes do not balance all the energy of those relations, and this excess energy determines the boundaries' properties. An example of this is hydrophilic and hydrophobic surfaces. In the former case, there is excess energy (hydrogen bonds) available so water can easily couple to the boundary. In contrast a hydrophobic surface has non-polar molecules at the surface. These don't have the potential for hydrogen bonds so water does not attach to the boundary.

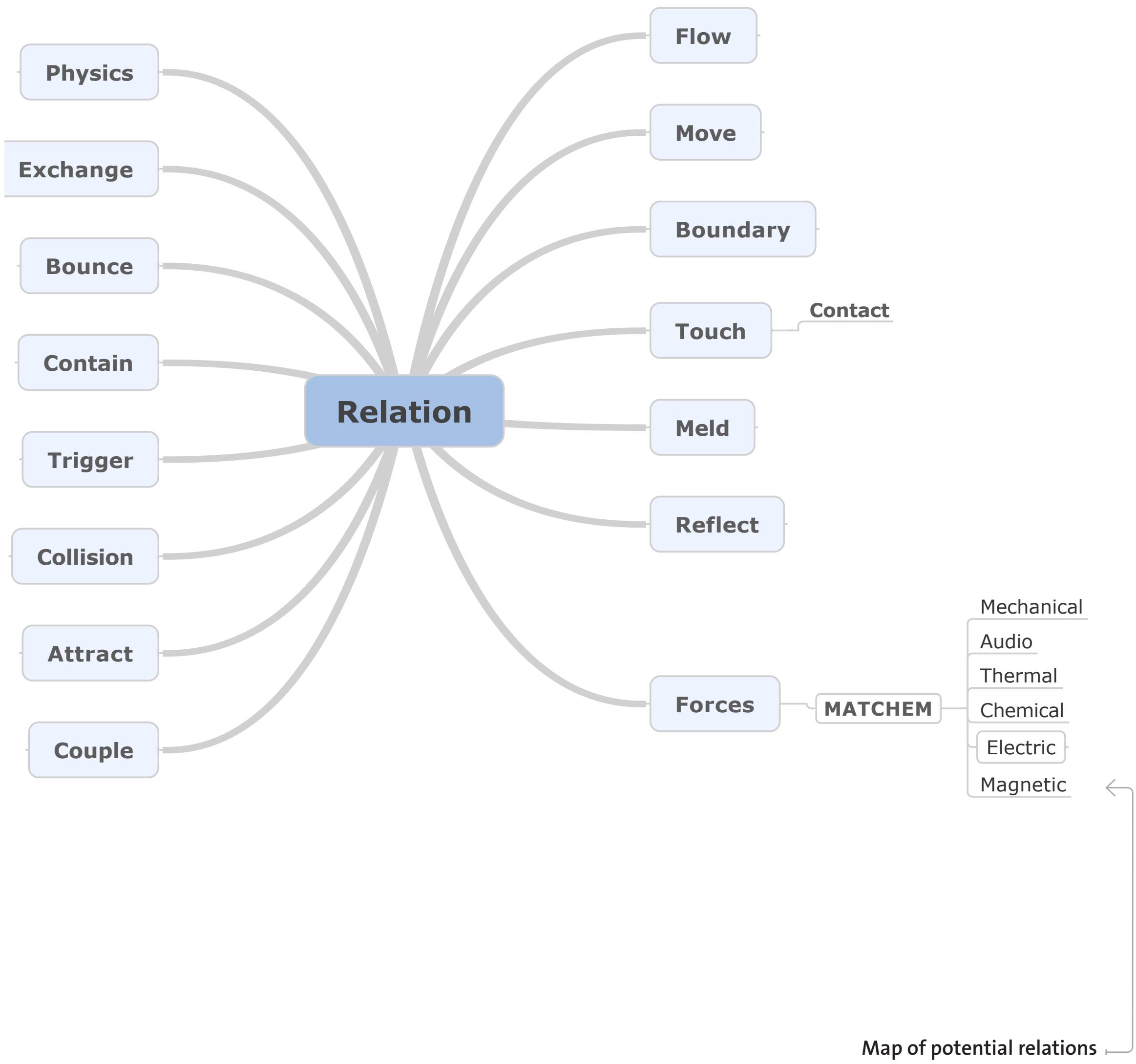
I believe that Nature builds structure in living systems for a reason: to enclose, to protect, to message. The outer surface of a structure is a boundary composed of nodes connected via relations. For example, when the form of C60 was discovered, researchers knew from measuring the atomic weight that there were 60 carbon atoms. They also knew from the chemical nature of carbon how many bonds were possible at a given atom (node). The result of these two constraints was the structure known as buckminsterfullerene.

In effect all structure is based on triangulation. At higher levels of scale the triangulation may be obscure enough that other shapes appear. At a fine grain, however, the triangulation is clear. Structures like a cube can appear to be stable, however each one is stabilized by internal triangles in the material they are composed of. This can be seen easily by building a cube of edges with flexible corners. It will collapse unless triangulation is added. Adding two tetrahedrons internally to the cube will stabilize it, and illustrates a more realistic view of the structure. While this area of synergetics has had some exploration, I believe a wider application of these principles will result in many new discoveries.

Tensegrity

Tensegrity is a word Fuller coined to describe minimal structure using coupled (and balanced) tension and compression. "Tensegrity is a building principle that was first described by the architect R. Buckminster Fuller and first visualized by the sculptor Kenneth Snelson. Fuller defines tensegrity systems as structures that stabilize their shape by continuous tension or "tensional integrity" rather than by continuous compression (e.g., as used in a stone arch)." (5)

Donald Ingber, Wyss Institute for Biologically Inspired Engineering and Harvard Medical School, has used the principle to explore the ways cells move and respond to their environment. "The cellular tensegrity model proposes that the whole cell is a prestressed tensegrity structure,



Map of potential relations

Courtesy of Curt McNamara

Little gecko (recent foot)

Photo: p for petrina, 2012 | Flickr cc

although geodesic structures are also found in the cell at smaller size scales (e.g. clathrin-coated vesicles, viral capsids). In the model, tensional forces are borne by cytoskeletal microfilaments and intermediate filaments, and these forces are balanced by interconnected structural elements that resist compression, most notably internal microtubule struts and ECM adhesions." (5)

Stephen Levin, MD, a proponent of "bio-tensegrity", has used the idea to model biological structures: "Tensegrity icosahedrons are used to model biologic organisms from viruses to vertebrates, their cells, systems and subsystems. There are only tension and compression elements in tensegrity systems. There are no shears, bending moments or levers, just simple tension and compression, in a self organizing, hierarchical, load distributing, low energy consuming structure." (6)

Tom Flemons, Intension Designs, describes tensegrity this way: "Tensegrities are all about tension and compression. Every structure, whether an artifact created by intelligence or a living form evolved by natural selection, is a balance between these two and only these two forces... Tensegrity is a scientific principle that describes natural geometry in terms of compression and tension vectors. It describes structures organized at the atomic, molecular and cosmological scales."

"Engineer and architect Mario Salvadori points out in his book *Why Buildings Stand Up*, that shear is equivalent to tension and compression forces acting at right angles and is not a separate force. Tensegrities are special case structures where the play of these two forces is visible in the design." (7)

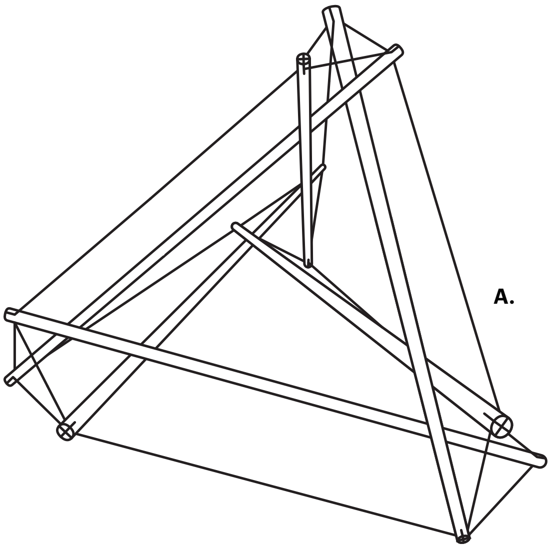
Tensegrity, therefore, has been explored to some level of detail for biological systems, as can be seen from the above quotations. Snelson (8) has also applied these ideas to the structure of the atom, and this approach remains to be explored.

Coordinate System

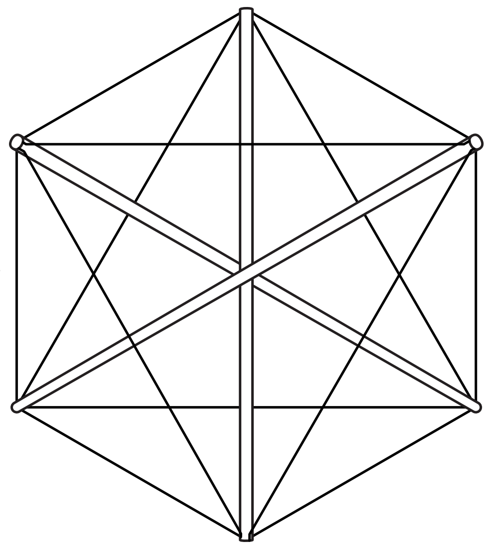
In my view, the standard mathematical basis for design is practical and efficient, but does not match the principles by which matter is constructed. For example, the Cartesian coordinate system with perpendicular axes does not represent nature. The result is that engineering and the sciences work with approximations. This keeps us from finding the shape of space at a very fundamental level. Since the Cartesian system is the basis for most mathematical education, students are getting an incomplete description of nature.

What is the coordinate system of structure and universe? If it is not the Cartesian coordinates of XYZ (as this does not fit biology) – then what is the best fit? The polar coordinates of r and theta come closer, showing how growth could extend from a point outwards into space.

The arrangement of elementary components is the underlying basis of material creation and organismal growth, When Fuller explored this, he concluded that closest sphere packing of twelve around one would fill all space. When the centers of the 12 spheres are joined, it forms a structure called a cuboctahedron (alternating square and triangular elements). This structure can be extended in all directions to fill space. When



A.



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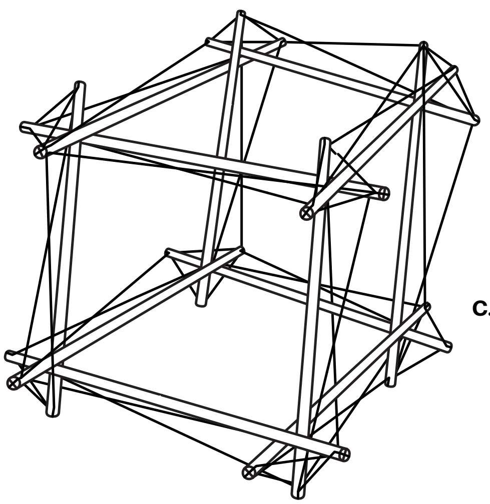


C.

a. A six-strut tensegrity tetrahedron shows central-angle turbining.

b. The three-strut tensegrity octahedron. The three compression struts do not touch each other as they pass at the center of the octahe-dron. They are held together only at their terminals by the comprehensive, triangular tension net. It is the simplest form of tensegrity.

c. The 12-strut tensegrity cube, which is unstable.

Text: http://www.rwgrayprojects.com/synergetics/s04/figs

Graphic: Colin McDonald

Bumble bee

Photo: Mike Legend, 2009 | Flickr cc

the center sphere is connected to the 12 outer spheres, the axes define what Fuller termed the Isotropic Vector Matrix (IVM).

The same arrangement of vectors can be seen in the octet truss invented by Alexander Graham Bell in the 1930's, and the typical space frame used in building construction. The simplest form of this is the combination of an octahedron with a tetrahedron, repeated in two or more directions.

While this form has been extensively explored for buildings and structures, it has not had much application in biomimicry. Since the form is the most minimal structure to fill space, it would seem to have many biomimicry applications. One application is in crystal formation in which face centered cubic structures are created. The perception that crystals are static and fixed over time may have contributed to this lack of applications in biology. This is also a misconception about synergetics in general: geometric structures are not static over time, rather forms can emerge and decay in picoseconds.

Given that the IVM fills all space, it is the simplest coordinate system of universe. The lines from the center node to the corners define 6 axes or 12 degrees of freedom. This may seem counterintuitive as we are familiar with the three axes, and using 6 seems more complex. However, fitting nature into 3 orthogonal axes yields, at best, an approximation. Working outwards from the center to the corners of the IVM is the most efficient use of material to create structure. While these axes have been discussed from a philosophical standpoint, biomimicry applications remain to be explored. (9)

Systems and interconnection

Systems are distinct from their environment. This distinction is determined by the boundary. In the boundary, relations between nodes are stronger than relations to the external world. A boundary contains ports that allow material, energy, and information to flow across, or to trigger processes within the system.

There is never complete cancellation of forces at a node. There are strong connections between the boundary elements and the system, however there is always excess energy at the nodes. This excess energy is what allows systems to couple together. Fuller referred to this as precession. Precession is "coupling at an angle". For example, a spinning top will stand upright. The orbit is circular, and produces a force at 90 degrees to align with gravity.

A good example of precession is the bumblebee and the flower. The bee intends to get nectar or pollen for sustenance, and picks up pollen as a consequence of her activity. This pollen gets transferred to another flower, and pollination occurs. This process is beneficial for both the flower and the bee. This is one biomimicry example of message passing or communicating between systems. I believe that a survey of plant / pollinator interactions will yield many ideas for improved communication design. (10)

Contact at a node (or nodes) is how systems couple together at the surface, and many biomimicry applications are at this level. Examples include hydrophobic surfaces (Lotusan Paint), adding bumps along edges to ease flow (Whalepower turbine), the jagged edge of the mosquito proboscis (hypodermic needle), and the gecko fine surface structure (gecko tape).

One way to explore an interface is to describe the types of relations that exist at the surface, bonding system elements together and then do a survey of forces to see which are being used and which are not. One might ask, therefore, what forces are available at the surface and have not been used?

Another example of coupling and shape comes from the simplest system: tetrahedrons can be coupled together on their sides to form a tetrahelix. This structure spirals around a central line, and a pair of tetrahelixes appears similar to the double helix of DNA.

Summary

This article has explored some of Buckminster Fuller's fundamental ideas about the shape of space and the laws of relation that govern how components are formed into structure. While system coupling via precession and relations has been partially explored in biomimicry, many more applications exist. Tensegrity applications have been explored by several researchers, and these ideas can be expanded further and applied. The shape of space is determined by the properties of relation, and this leads to the fundamental coordinate system of structures and space. This has not been explored fully, and many applications are possible. ×

References

1. Baldwin, Jay. *Buckyworks: Buckminster Fuller's Ideas for Today*. (Wiley, 1977)

2. http://www.rwgrayprojects.com/synergetics/synergetics.html

3. French, Michael. *Invention and Evolution: Design in Nature and Engineering*. (Cambridge, 1994)

4. Hinds, Bruce and Hastrich, Carl. *Course Materials for Ontario College of Art and Design*

5. http://www.childrenshospital.org/research/ingber/Tensegrity.html

6. http://www.biotensegrity.com/index.php

7. http://www.intensiondesigns.com/

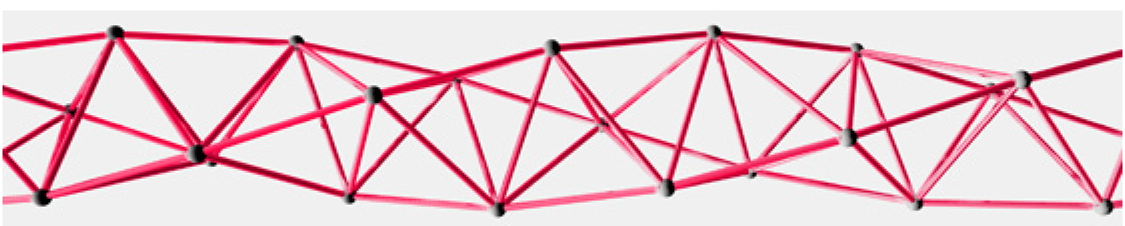
8. http://www.kennethsnelson.net/

9. Edmondson, Amy. *A Fuller Explanation*

http://books.google.com/books?id=F6n2dZJ1POwC&printsec=frontcover&vq=ivm#v=onepage&q=ivm&f=false

10. McNamara, Curt

http://www.linkedin.com/pub/curt-mcnamara-m-eng-p-e/3/b21/b89

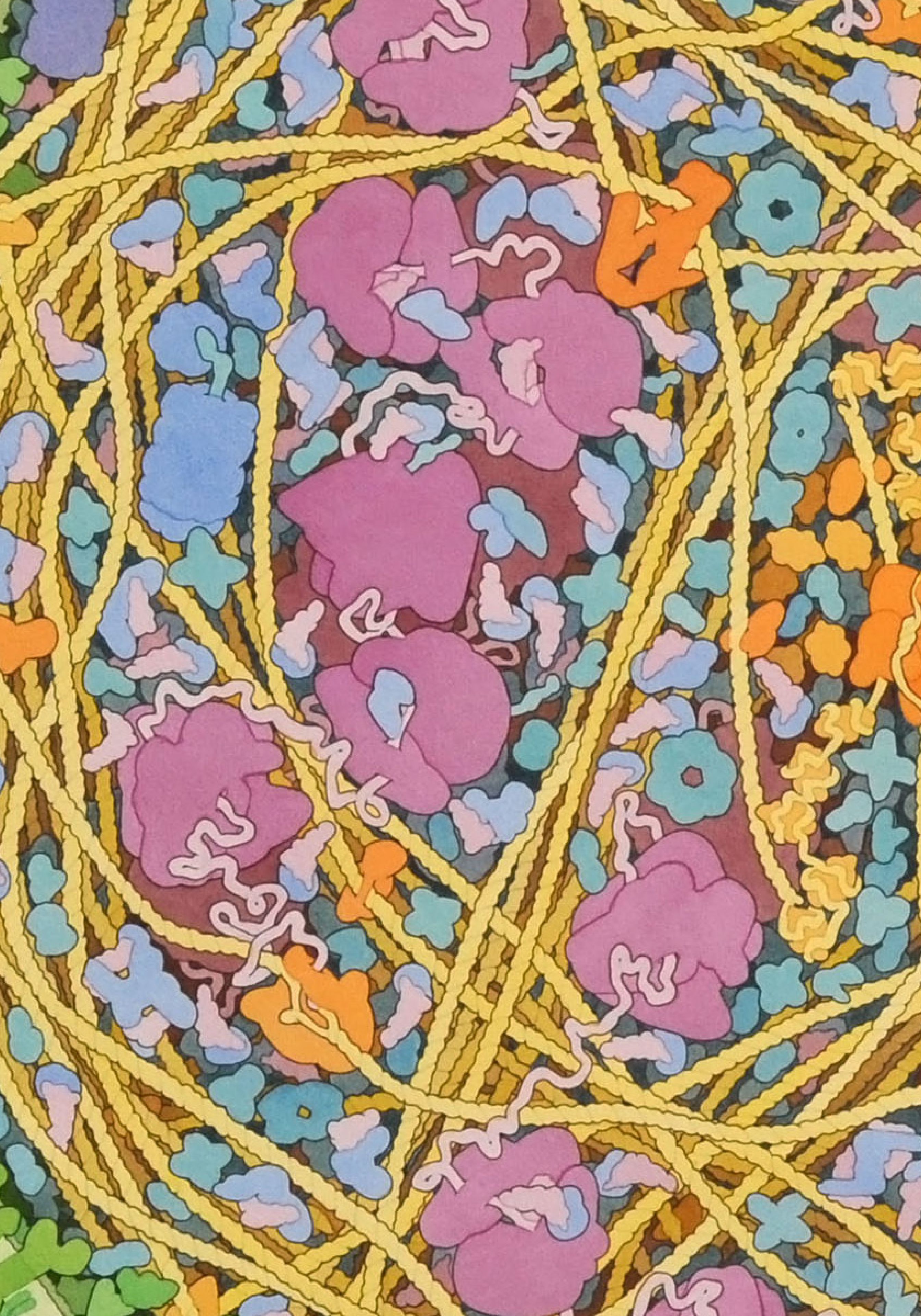


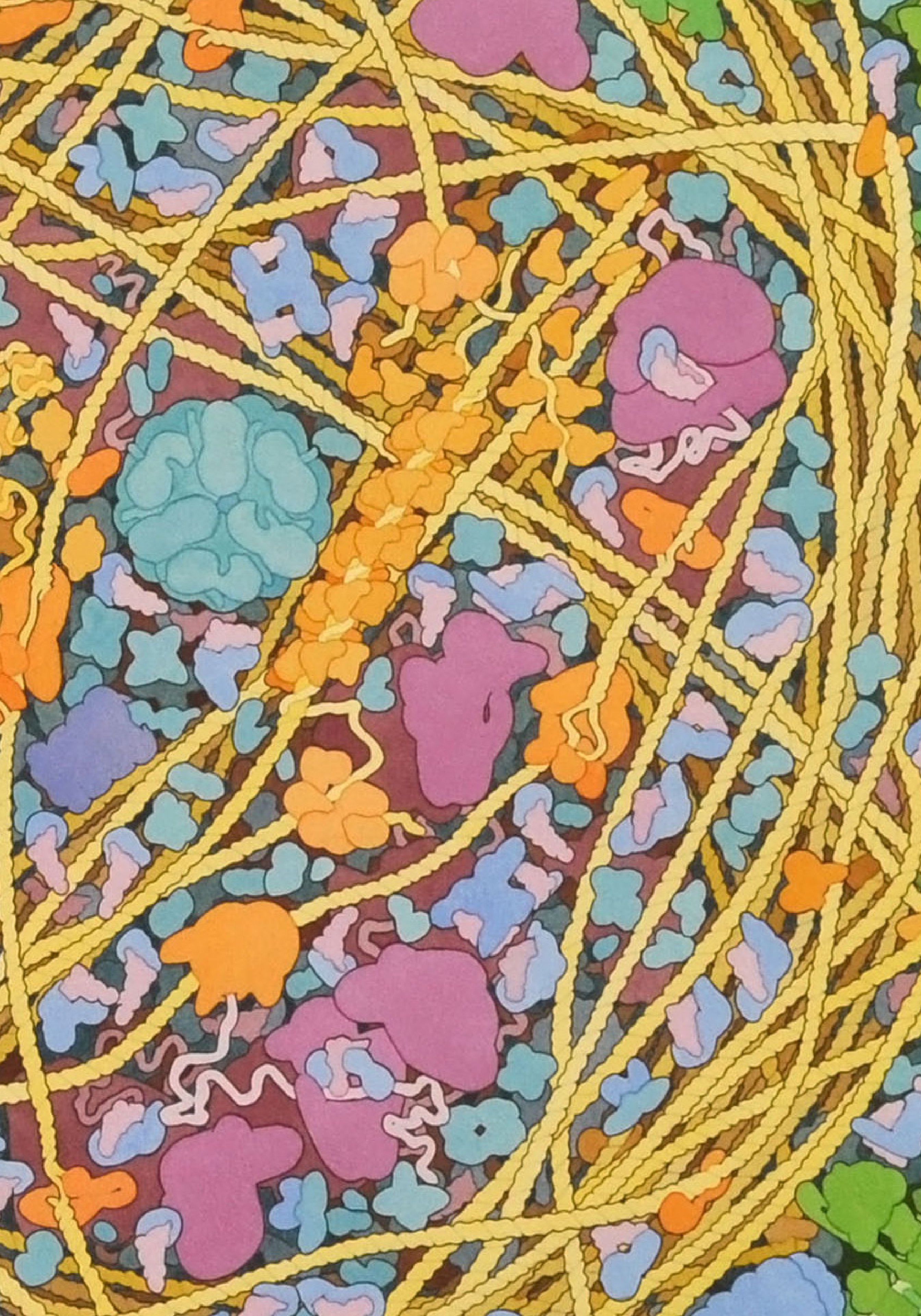
Coxeter-Boerdijk-helix (tetrahelix)

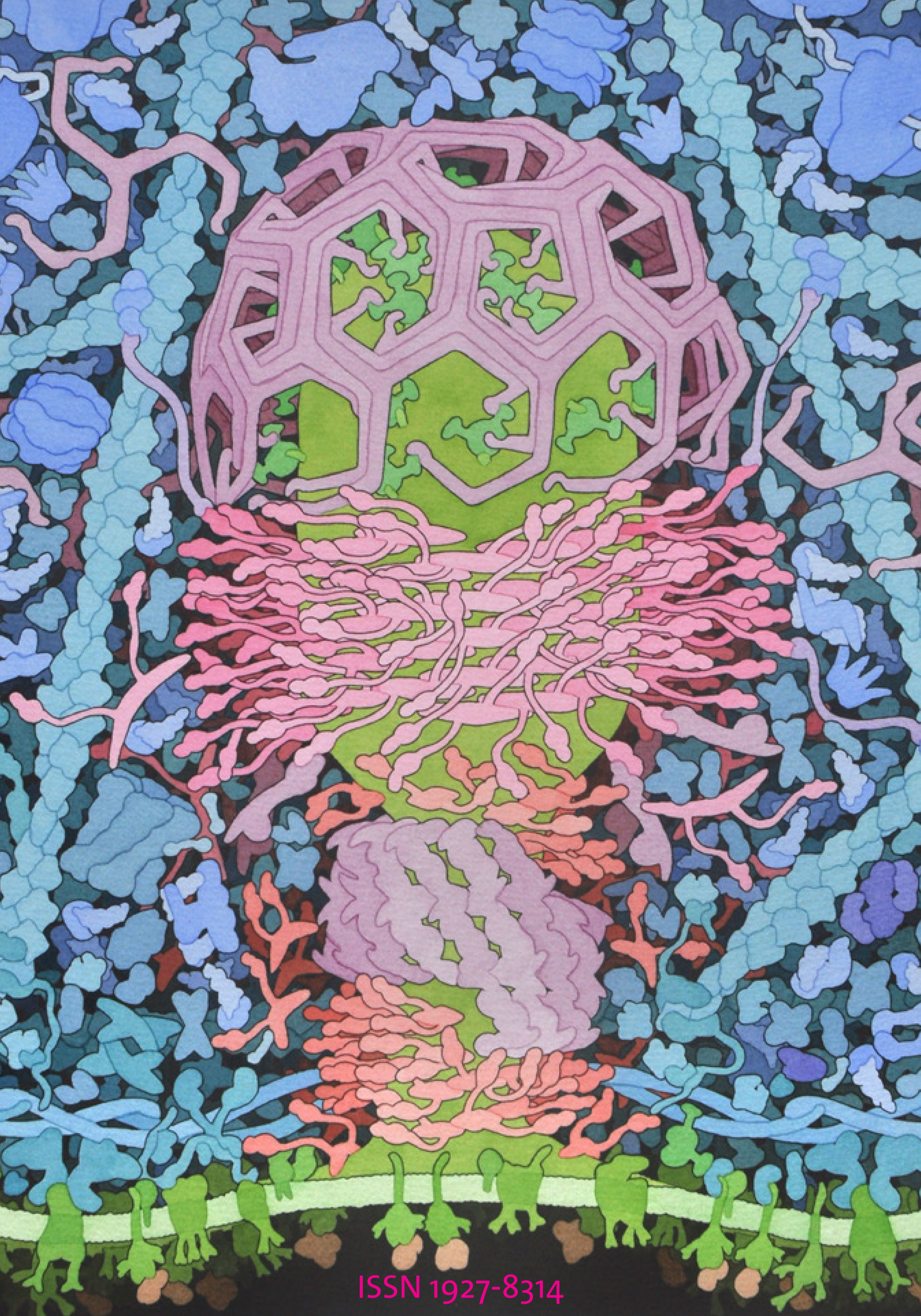
Photo: fdecomite, 2009 | Flickr cc

Untitled (Humpback whale)

Photo: cheesy42, 2008 | Flickr cc







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