ARTIST'S NOTE

Protein Sculptures: Life's Building Blocks Inspire Art

Julian Voss-Andreae

ABSTRACT

The author takes a literal look at the foundation of our physical existence by creating sculptures of proteins, the universal parts of the machinery of life. For him, it is less important to copy a molecule accurately in all its details than to find a guiding principle and follow it to see whether it yields artistically interesting results. The main idea underlying these sculptures is the analogy between the technique of mitered cuts and protein folding. The sculptures offer a sensual experience of a world that is usually accessible only through the intellect.

There is in Nature a limitless variety of shapes and rhythms (and the telescope and microscope have enlarged the field) from which the sculptor can enlarge his form-knowledge experience.

—Henry Moore [1]

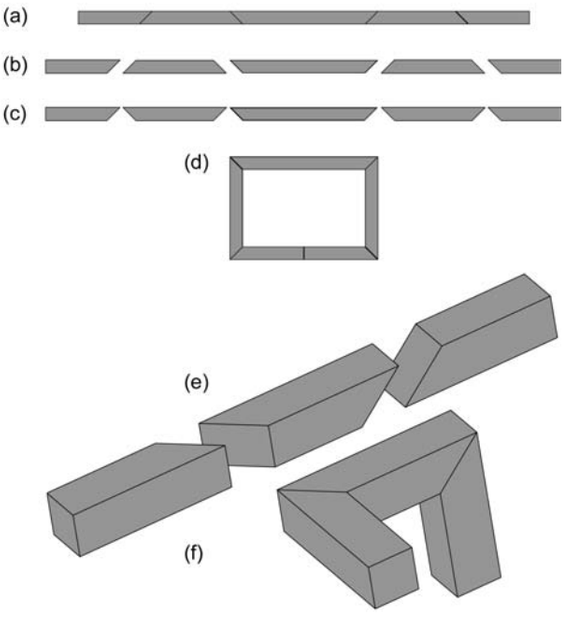
In his 1968 book *Beyond Modern Sculpture,* the visionary author Jack Burnham asserted, "In a very real sense [D'Arcy W. Thompson's book] *On Growth and Form* [2] stands on the threshold between that world of natural forms which is still accessible to the sculptor, and the world of molecular bonds and protein chains completely out of his reach" [3].

What Burnham did not take into account at the time of this assessment was the rapid advancement of technology that would one day provide artists with the tools necessary to gain inspiration from nature beyond what can be seen by the unaided eye. One generation after his writing, powerful computers came into widespread use. At the same time, experimental techniques came to routinely resolve structures on a subatomic scale, and laboratories started making their experimental results accessible on the Internet. Today anyone with a computer can, in principle, download tens of thousands of different protein structures [4] and create highly illusionistic three-dimensional renditions of these data.

PROTEINS

Both life and inanimate matter consist of atoms. Atoms are the building blocks from which all the matter that surrounds us and all the matter we experience as "ourselves" is made. Atoms combine to form molecules. Molecules encountered in biochemistry differ considerably, for the most part, from molecules found in inanimate matter. The fundamental molecule of life is DNA, which contains the "blueprint" for each organism's form as well as for its function. The double helix, with its sequence of base pairs, is essentially a one-dimensional [5] strand of information. Every triplet of base pairs in a gene codes for one of the 20 different amino acids that are the building blocks of life. Proteins, chains of linked amino acids, are the next level of important building blocks. The physical properties of the different amino acids cause them to fold and wind into well-defined 3D configurations determined by their sequence. The process of protein biosynthesis and folding is the point at which life makes the transition from one-dimensional DNA into three-dimensional bodies. Proteins play a key role in structure and function from cell to organism. The diverse structures of proteins give rise to a stunning variety of functions [6]. Enzymes, an important class of proteins, are catalysts needed to regulate all biochemical reactions. In vertebrates the antibodies form a major line of defense against foreign organisms. Our every movement results from the contraction and relaxation of muscles, resulting in turn from the

Fig. 1. The principle of mitered cuts. (© Julian Voss-Andreae) A picture frame is constructed by cutting a one-dimensional piece of wood (a) at 45° (b), flipping every other piece (c), and reassembling the pieces in the same order (d). Mitered cuts can be applied such that the material occupies all three dimensions after reassembly (e and f).



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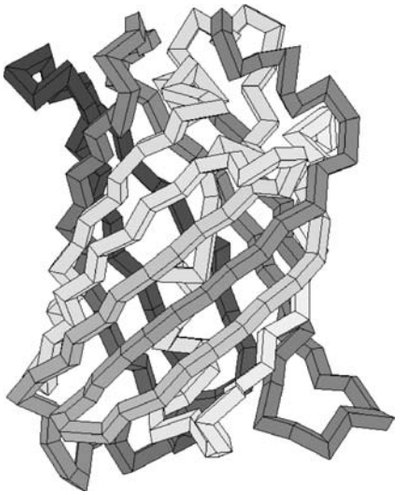

Fig. 2. Virtual model for a sculpture of the Green Fluorescent Protein GFP [1emg]. (© Julian Voss-Andreae) This protein makes a certain jellyfish glow green in the dark and is used extensively in biological research. Its structure, a bird-cage-like barrel made up of 11 bars spiraling up and down the surface of a cylinder, is extraordinarily beautiful. The peptide chain is rendered in different shades of gray to aid in the recognition of the complicated structure.

delicately regulated sliding of specific proteins in muscle cells past one another. Still other proteins act as adjustable channels through which ions are passed from one side of a membrane to the other, resulting in phenomena such as the transmission of electric signals along nerves, which is the physical basis of our thoughts and our senses.

PRINCIPLE

One of the fundamental properties of proteins is that they are 3D objects despite their essentially one-dimensional structure. We are familiar with similar phenomena in our everyday lives. An example is a piece of wire bent many times into a compact 3D shape. A rigid material like a piece of lumber, however, can also be "folded" by applying mitered cuts and reassembling it. For instance, an object such as a picture frame is constructed in this fashion by cutting a long piece of wood four times at 45° (see Fig. 1a–d). The pieces are glued together in the same order after every other piece is rotated 180° around the length of the wood, which results in a "folding" of 90°—that is, twice the cutting angle. The picture frame example is still only 2D, but it is also possible to produce an object occupying all three dimensions by cutting at different angles (see Fig. 1e–f). The piece so reassembled is essentially the same as before, because no material was added or lost. It extends into three dimensions only by virtue of a rearrangement of its parts. The principle of creating sculptures through the technique of mitered cuts lends itself very well to representing protein structures, because both share the fundamental property of being one-dimensional objects occupying three dimensions. It is surprisingly difficult to make miter-cut sculptures using a preconceived plan, but the well-defined geometric properties of miter-cut sculptures allow for a computational treatment of the problem.

REALIZATION

I developed a computer program that allows me to turn any given sequence of 3D points into a miter-cut sculpture [7]. The software renders the sculptures realistically from any point of view, allowing me to rotate the virtual object at will and look at it as if it were in real space (see Color Plate D No. 2,e and Fig. 2). My program also provides me with detailed cutting instructions by computing all angles and lengths needed for a physical realization of the sculpture. A list containing the positions of the four points of intersection between each cutting plane and the material's edges is generated. This allows for an easy marking of the correct distances along the edges. The marks are then connected (with the additional control of an angle measurement using a protractor), and the material is cut along the lines and reassembled.

A protein structure database [8] provides my program with the position of each amino acid. The amino acids in the protein form a chain of identical flat rectangular units called peptide units [9]. Particular carbon atoms, usually denoted with the subscript α, connect these units. The amino acids do not differ in the peptide units making up the backbone of the protein. The difference lies only in the side chains departing from the C_α atoms, whose physical properties are the key force guiding protein folding. I use the positions of the C_α atoms [10] to compute cutting instructions. That means that each piece of the sculpture, extending from the center of one joint to the next, corresponds to one peptide unit in the molecule.

SCULPTURES

My first sculpture was a small (58-amino-acid) protein called Bovine Pancreatic Trypsin Inhibitor (BPTI) [1bpi] [11], a protein that inhibits the digestive enzyme trypsin in cows. I first came across BPTI in a physics journal [12], which showed the protein using different kinds of models (see Color Plate D No. 2,a–d), illustrating the problem one encounters in visualizing these structures. Color Plate D No. 2,a shows all atoms rendered as spheres. Color Plate D No. 2,b and Color Plate D No. 2,c emphasize the chemical

Fig. 3. *Kalata*, painted steel, length 3 ft, 2002. (© Julian Voss-Andreae) The sculpture was welded from 2-×-2-in square steel tubing and spray-painted in blood red. The uteroactive protein Kalata B1 [1k48] has been isolated from traditional African herbal medicine, where it is used to accelerate labor in childbirth. The cyclic structure consists of 29 amino acids and has the same topology as the Möbius strip.

Fig. 4. ***Large Fir Alpha Helix*****, Douglas fir and steel, length 11 ft, 2002. (© Julian Voss-Andreae) The sculpture was made out of a 33-ft piece of a 40-year-old tree.**

structure of the molecule. The path of the backbone is colored from red to orange, yellow, green and blue, and the side chains are gray. The rendition in Color Plate D No. 2,d, the so-called ribbon model, emphasizes the backbone of the protein and comes therefore the closest to depicting a protein as a miter-cut sculpture, shown in Color Plate D No. 2,e and Color Plate D No. 2,f. Color Plate D No. 2,e is the virtual model of the same protein rendered by my computer program and displayed from the same point of view as Color Plate D No. 2,a–d. Color Plate D No. 2,f is a photo of the 15-in-high sculpture *BPTI* (2001). I chose this protein to experiment with the technique and to get a feeling for how a virtual sculpture compares to a real one. The material is wood with a cross section of ¾ × ¾ in. The cuts on the 9-ft-long piece of wood were done with a handsaw, and the pieces were glued together. The sculpture was then spray-painted ultramarine blue and the spiraling parts (the so-called α-helices) warm cadmium yellow to balance the visual tension present in the standing piece.

My next project was *Green Fluorescent Protein (GFP)* [1emg] [13]. This protein from the Pacific Northwest jellyfish *Aequorea victoria* consists of almost 240 amino acids arranged in a beautiful birdcage-like structure (see Fig. 2) [14]. GFP had initially sparked my interest in protein structure when, as a graduate student in Anton Zeilinger's research group in Vienna, Austria, I investigated the possibility of using it to extend the demonstration of quantum mechanical wave behavior from Buckminsterfullerenes (C_{60}) [15,16] to large biomolecules [17]. GFP is one of the most widely used proteins in biological research because it is expressed readily in many organisms after gene transfer, allowing it to be used as a marker of gene expression and protein targeting [18]. The possibility of creating animals that glow green under ultraviolet light by inserting the GFP gene into their genomes [19] has attracted not only scientists. The creation of a GFP rabbit by Eduardo Kac as a piece of "transgenic art" has recently surprised the art world [20] and triggered heated debates. I began two GFP wood sculptures, but because of the low accuracy of the power saw I used and the large number of amino acids, which led to an accumulation of errors, it proved impossible to assemble the pieces as originally planned [21].

For my next material I moved on to steel, which allows for accurately machined cuts with strong welded joints. I chose the cyclic protein Kalata B1 [1k48] [22], a 29-amino-acid-long molecule found in the African plant *Oldenlandia affinis*. Traditional African herbal medicine uses extracts of *O. affinis* to accelerate labor in childbirth, and Kalata B1 is the main uteroactive agent [23]. The sculpture shown in Fig. 3 was built from 2-×-2-in square steel tubing and finished in a glossy red, alluding to the blood of childbirth.

Any material where the shape of the cross-sectional area looks identical after a rotation of 180° is suitable for miter-cut sculptures. Therefore materials with a circular cross-section, such as tree trunks, can also be used. Wood, like steel, is a major building block material in human construction and can therefore serve in an analogy to the building-block character of proteins. For my next protein sculpture I used a 33-ft-long piece of a trunk of Douglas fir, the most commonly used lumber wood in the United States [24]. In addition to wanting to work on a much larger scale, I wanted to explore the pos-

Fig. 5. ***Tall Fir Alpha Helix*****, Douglas fir and steel, height 10 ft, 2003. (© Julian Voss-Andreae) Unlike in the alpha helix shown in Fig. 4, the cuts in this sculpture are applied very close to one another to yield the highest possible density. The right panel shows a detail.**

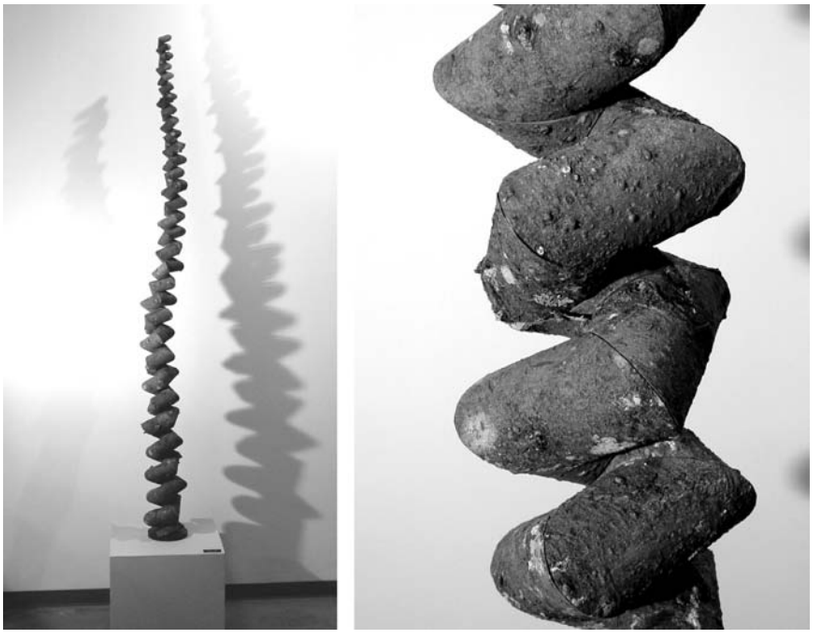

Fig. 6. ***Green Fluorescent Protein*****, steel with process marks, height 5 ft 6 in, 2004. (© Julian Voss-Andreae) This sculpture is a physical realization of the virtual model shown in Fig. 2, made from 100 ft square steel tubing.**

sibility of creating an object out of identical subunits. The α-helix, which forms the spiraling part of proteins such as the ones seen in the BPTI structure (see Color Plate D No. 2), is an ideal choice, as it is one of the most abundant structural elements found in proteins. A straight fir that had recently died was felled and cut into identical pieces with a chain saw. The two angles determining each cut were measured with custom-built devices [25]. I used three brackets welded from ¼-in steel attached with 10 large screws for each connection between the pieces to create joints strong enough to support the wood's enormous weight. The tree was left in its original state, with bark and lichen on it, to enhance the contrast between the natural tree and its forced rearrangement (see Fig. 4).

For a second α-helix sculpture, a 26-ft-long dead Douglas fir was felled and cut into over 100 pieces. This time I consciously diverged from making an accurate model of the protein element by successively shortening the length of the pieces proportional to the decreasing diameter [26]. The pieces were then reassembled as a vertically standing spiral. The accumulation of small errors in combination with the organic shape of the tree caused the piece to assume a beautiful organic movement with a striking resemblance to a human spine (see Fig. 5). The emergence of such an unexpected new level of meaning is highly welcome. In addition to its intellectual side, my work has an equally strong intuitive and irrational side that causes my pieces to stop working as scientific models and become pure art objects.

SIGNIFICANCE

The demonstration of the in vitro synthesis of urea in the early 19th century showed that, contrary to the leading paradigm of that time, organic chemistry is not confined to living organisms. Today we witness the isolation, transfer between organisms and expression of single genes encoding particular proteins. Genetic engineering is, like the synthesis of urea, just another step in the merging of two traditionally separate fields: life and a technology based on life's building blocks. Life's building blocks are generally considered inanimate and therefore perceived as fundamentally different from life. It is interesting to associate life and its building blocks with the poles *organic* and *constructive*, using a conception from sculpture theory. Herbert Read, who was one of the major theoreticians to promote the interpretation of the history of sculpture as an oscillation between organic and constructive tendencies, made this connection explicit in 1952: "We have seen that constructive elements underlie all natural phenomena; that organic growth follows laws, and involves structures, which are as geometrical, or mathematical, as anything created by a constructivist artist" [27]. My protein sculptures have aspects of both organic and geometric objects. Like real proteins, my sculptures consist of "constructive" building blocks with very simple geometry, but become "organic" by virtue of the rearrangement of the parts in complex ways.

Works in both science and art embody the most fundamental expressions of the human spirit. My work is an exploration and probing of the accepted divide between science and art as either primarily intellectual or primarily emotional. The sculptures presented in this article play on the sensuality and beauty that underlie sense and being itself.

POSTSCRIPT

Since writing this article, I became aware of other sculptors who present physical realizations of proteins in a fine art context [28]. Byron Rubin, a crystallographer, who invented a tool ("Byron's Bender") for making protein models from bent wire, is a pioneer in the field of making protein sculptures. The small wire structures made with his tool were the easiest to manipulate and most portable models available at the time. They became very popular among researchers before computers were capable of providing them with virtual models and were

the source of several important scientific insights [29]. Sculptor Mara G. Haseltine recently created a large-scale piece called *Waltz of the Polypeptides* (2003), which portrays the biological creation of a protein. The sculpture consists of stylized ribosomes, with the protein represented as a ribbon model [30].

I finished writing this article in the spring of 2003, and I have since created several new protein sculptures. These include a 5-ft-6-in-tall steel *GFP* (Fig. 6). This sculpture, a physical realization of the virtual model shown in Fig. 2, was made from 100 ft square steel tubing. The numbers that were used to enumerate the joints of this piece can still be traced through the entire length of the steel tubing. Certain chemical bonds (hydrogen bonds), which account for the stability of the molecule, are represented by ¼-in rods, connecting the square tubing in the barrel-like structure. The spiraling movement of the rods runs perpendicular to the movement of the tubing, resulting in a visual dynamic that emphasizes the beauty of the molecule. I have also created an outdoor steel sculpture based on the a-helix. This piece was created to honor the memory of Linus Pauling, the discoverer of the α-helix, and stands in front of his childhood home in Portland, Oregon. The 10-ft-tall piece, which was commissioned by the Linus Pauling Center for Science, Peace and Health, was made from a 20-ft steel beam with a 12-×-12-in square cross section, cut into 15 pieces. The piece was powder-coated in primary red, complementary in color to the green foliage embracing it. The vertically standing *Alpha Helix* appears to be balancing on one corner, which, along with its location in a busy urban environment, makes it especially visually striking [31].

An extensive account of how my work evolved can be found in my B.F.A. thesis paper [32], which is downloadable from my web site [33]. The paper also contains a historical overview and an appendix with instructions for building one's own protein sculptures.

Acknowledgments

I want to thank my wife Adriana, who sparked my passion for proteins when she introduced me to GFP (which she uses routinely in her neuroscience research) and helped me greatly in editing this manuscript. I also want to thank Jeff Baker, my fellow student in my first semester at the Pacific Northwest College of Art in Portland, Oregon, whose densely packed mitered woodcut sculpture reminded me of a globular protein and led me to explore the renditions of proteins as such sculptures. Michael May and Linda Wysong read the manuscript and provided me with helpful comments. Helmut Grubmüller and Matthias Rief were kind enough to let me use their instructive picture of BPTI (Color Plate D No. 2a–d) from their article [34]. The Douglas firs used in the α-helix sculptures were a kind gift from Roger Cone.

References and Notes

1. Quoted in Herbert Read, *A Concise History of Modern Sculpture* (New York: Praeger, 1964) p. 30.

2. D'Arcy W. Thompson, *On Growth and Form*, J.T. Bonner, ed., Abridged Ed. (Cambridge, U.K.: Cambridge Univ. Press, 1961).

3. Jack Burnham, *Beyond Modern Sculpture: The Effects of Science and Technology on the Sculpture of This Century* (New York: George Braziller, 1968) p. 77.

4. H.M. Berman et al., "The Protein Data Bank," *Nucleic Acids Research* **28** (2000) pp. 235–242 <http://www.rcsb.org/pdb/>.

5. If a physical object is referred to as being "n-dimensional"(or "nD"), it means that it extends *significantly* only into n of the 3 dimensions of physical space. Its extent into the remaining 3-n dimensions is negligible compared with the extent into the other n dimensions, i.e. smaller by some orders of magnitude. Therefore, a "three-dimensional object" has comparable length, width and height. A "two-dimensional object" stretches out mostly into two dimensions, and a "one-dimensional object" is much longer than it is wide and high.

6. William K. Purves and Gordon H. Orians, *Life: The Science of Biology* (Sunderland, U.K.: Sinauer Associates Inc., 1987) pp. 70–71.

7. The program performs successive multiplications of Euler matrices in order to rotate the coordinate system describing the orientation of the material along the protein backbone. The cutting angles are computed from the azimuth and the polar angle at each point.

8. I use the Protein Data Bank [4] <http://www.rcsb.org/pdb/>. After a suitable protein has been found it can be viewed three-dimensionally (by using "Explore" → "View structure" → "Quick pdb") and downloaded as a set of Cartesian coordinates for each atom in the molecule.

9. Carl Brändén and John Tooze, *Introduction to Protein Structure* (New York: Garland Publishing, 1991) p. 4.

10. The C_α atoms are denoted "CA" in the .pdb files in the Protein Data Bank.

11. The name of the Protein Data Bank file containing the data is "1bpi.pdb".

12. Matthias Rief and Helmut Grubmüller, "Kraftspektroskopie von einzelnen Biomolekülen," *Physikalische Blätter* **57**, Heft 2, 55–61 (2001).

13. F. Yang, L.G. Moss and G.N. Phillips, "The Molecular Structure of Green Fluorescent Protein," *Nature Biotechnology* **14** (1996) p. 1246.

14. Vivienne B. Gerritsen, "Mirror Mirror on the Wall Who Is the Greenest of Us All?," *Protein Spotlight* **11** (2001) <http://us.expasy.org/spotlight/articles/sptlt011.html>.

15. Markus Arndt, Olaf Nairz, Julian Voss-Andreae, Claudia Keller, Gerbrandt van der Zouw and Anton Zeilinger, "Wave-Particle Duality of C_{60} Molecules," *Nature* **401** (1999) pp. 680–682; see <http://www.quantum.univie.ac.at/research/matterwave/c60>. The main page of Anton Zeilinger's group is found at <http://www.quantum.at>.

16. Julian Voss-Andreae, "Kohärente Molekülоptik mit Fullerenen," Diplomarbeit (Berlin: Freie Universität Berlin, 2000).

17. Lucia Hackermüller et al., "The Wave Nature of Biomolecules and Fluorofullerenes," *Physical Review Letters* **91** (2003) p. 90408.

18. Roger Y. Tsien, "The Green Fluorescent Protein," *Annual Review of Biochemistry* **67** (1998) pp. 509–544.

19. For two examples see: <http://www.tsienlab.ucsd.edu/> and <http://www.mshri.on.ca/nagy/>.

20. See <http://www.ekac.org/>.

21. Three years after this attempt, I displayed both "sculptures" under the title *Failed Biosynthesis*, because by then I had successfully completed a GFP sculpture in steel (Fig. 6), which I could show together with the failed ones.

22. L. Skjeldal et al., "Refined Structure and Metal Binding Site of the Kalata B1 Peptide," *Archives of Biochemistry and Biophysics* **85** (2002) pp. 142–148.

23. Vivienne B. Gerritsen, "The Protein with a Topological Twist," *Protein Spotlight* **20** (2002); <http://us.expasy.org/spotlight/articles/sptlt020.html>.

24. Warren R. Randall et al., *Manual of Oregon Trees and Shrubs* (Corvallis, OR: O.S.U. Book Stores, 1990) p. 71.

25. Photos of those devices and of the cutting procedure are published in my B.F.A. thesis paper, "Protein Sculptures" (Portland, OR: Pacific Northwest College of Art, 2004) and on my web site <http://www.JulianVossAndreae.com> ("work" → "archive" → "Protein Project II").

26. Because the pieces correspond to the peptide units, their lengths should be identical in an accurate model of a protein.

27. Herbert Read, *The Philosophy of Modern Art* (London: Faber & Faber, 1952) p. 201.

28. The *World Index of Molecular Visualization Resources* web site <http://www.molvisindex.org> gives an overview under "Physical Molecular Models and Molecular Sculpture."

29. Information on the history of the visualization of biological macromolecules can be found on Eric Martz and Eric Francoeur's interesting web site <http://www.umass.edu/microbio/rasmol/history.htm>.

30. See <http://calamara.com>.

31. The making of the piece was featured by the Oregon Public Broadcasting television series *Oregon Art Beat* (6 May 2004). A clip can be downloaded from my web site [25] ("work" → "archive" → "Protein Project V" → "click here").

32. See ref. [25].

33. See ref. [25] ("work" → "archive" → "BFA Thesis Paper").

34. Rief and Grubmüller [12].

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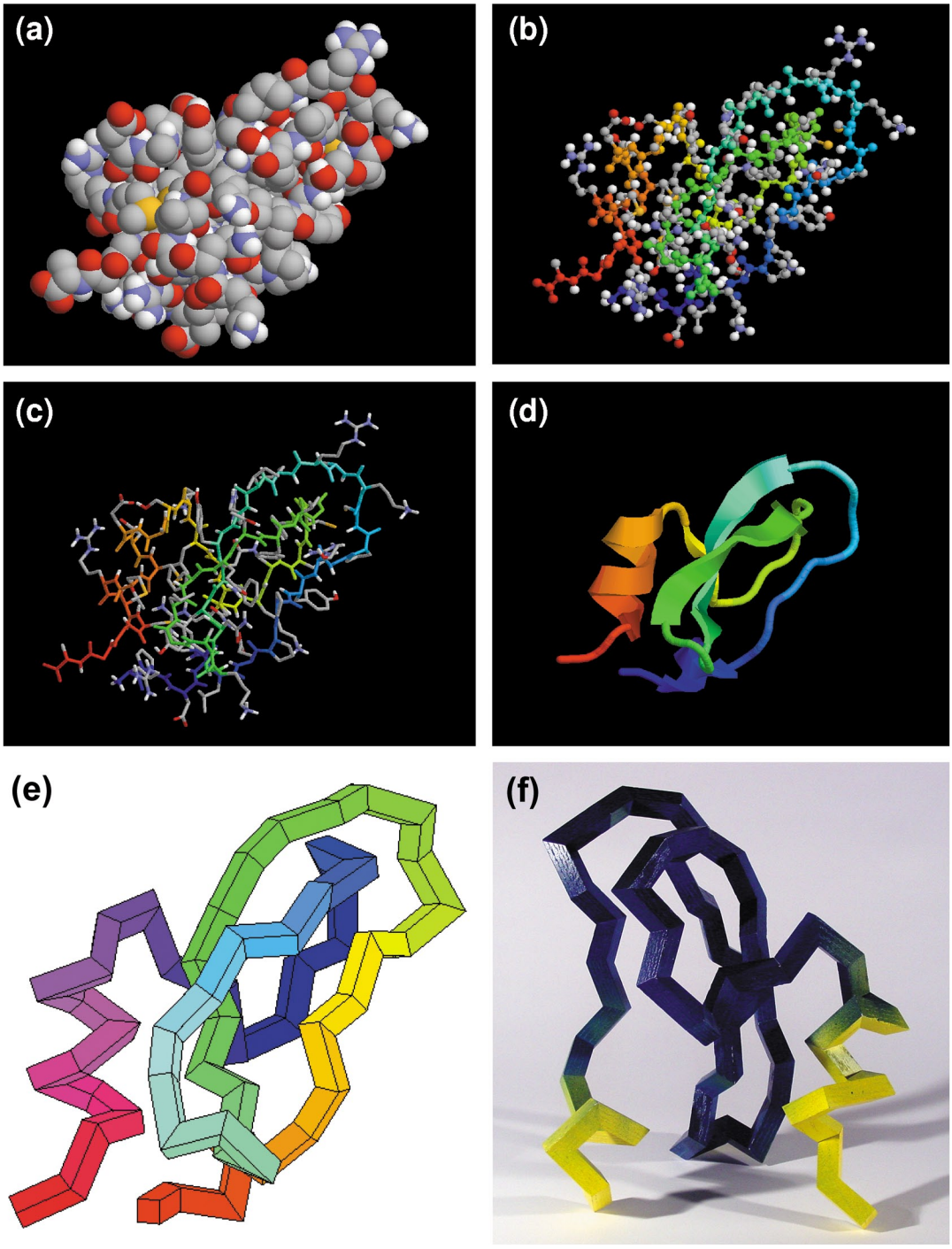
COLOR PLATE D



No. 2. Julian Voss-Andreae, the 58-amino-acid protein Bovine Pancreatic Trypsin Inhibitor (BPTI) in different renditions. (a) to (d) are the renditions typically encountered in the scientific literature. (© Wiley-VCH) (e) and (f) depict the same protein as mitered cut sculptures. (© Julian Voss-Andreae)