

# From Structure to Atoms

## *From Compression/Tension Systems to a Molecular Tensegrity*

J. DAVID VAN HORN AND DAYU WANG

ABSTRACT

The authors reconsider macroscopic structures, including tensegrity structures, as ensembles of compression and tension forces and fit these structures to a triangular spectrum. They then present a derivative structural analogy to the three classes of molecular bonding as a bridge to microscopic structure. The construction of tensegrity sculptures of particle interactions and covalent molecules using tension and compression components follows. The authors derive and utilize two properties in this analysis: (1) a “simplest tensegrity” subunit structure and (2) *interpenetrating*, discontinuous compressive components—the tension components may also be discontinuous in a structure. This approach provides new artistic models for molecules and materials and may inform future artistic, architectural, engineering and scientific endeavors.

### A SPECTRUM OF STRUCTURE

For millennia, humans have been constructing all types of utilitarian, artistic and architectural objects. These are formed from natural or modified materials that possess the character needed to adopt specific forms or functions [1,2]. Examples include a wheeled cart or an ax, a decorative serving bowl or a pitcher, and a tent or a Greek temple. In all cases, the object's structure consists of compression (C) and tension (T) interactions throughout and between the components making up the object [3]. We use the terms compression and tension in their usual physics sense, and we equate these terms to repulsion and attraction forces, respectively. Thus, an object in compression has internal repulsive forces acting against external forces pushing inward, and an object in tension possesses internal attractive forces to maintain its structural integrity.

Consider structure as existing on a spectrum composed of compressive and tensile force *networks*, acting together to form a three-dimensional object. This spectrum can be thought of as having four extremes: (1) continuous com-

pression/*discontinuous* tension networks; (2) continuous compression *and* tension networks; (3) *discontinuous* compression/*continuous* tension networks; and (4) both *discontinuous* compression *and* tension networks (Fig. 1). Here, “continuous” refers to a unified network of interactions with paths between all elements; “discontinuous” denotes separated or terminal elements and gaps in the networks of interactions [4,5]. We include the case with *discontinuous* C and T for completeness, but we set it aside because it does not lead to structure. Gravity is pertinent here and is considered a tensile, attractive force acting on objects and structures on earth. A zero-gravity environment, and how structures perform under this condition, is also relevant to the evaluation and use of any type of structure in the spectrum. Other forces—including torsion, shear and friction—are set aside to focus on three-dimensional C/T structures in static equilibrium.

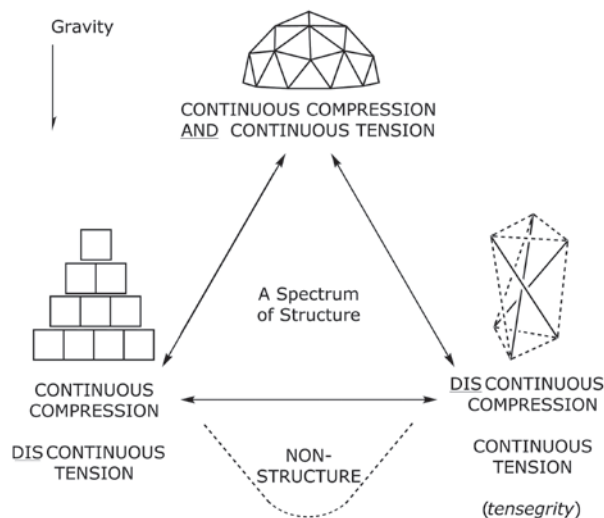
Examples of architecture exhibiting continuous compression but *discontinuous tension* include ancient monumental pyramids, certain arches and unmortared brick or stone chimneys (Fig. 1). In these structures, gravity provides a *separate* tensile force to each component but results in a continuous compression network throughout the structure. In a zero-gravity environment, these structures would gradually drift apart, having no internal tension elements.

Tensegrity is a *discontinuous* compression but continuous tension system that resides at the other extreme of discontinuity in our spectrum. This term was coined by R.B. Fuller from “tensional integrity” [6]; others define it as an “endoskeletal floating-compression structure” [7] or a “minimal self-tensile construction” [8]. Tensegrity encompasses the discontinuous compression structural systems discovered and described by Kenneth Snelson and others [9,10]. Tensegrity structures are “comfortable” in zero gravity, retaining their three-dimensional shapes *without* external influence. Nevertheless, on Earth these structures must have enough “tensional integrity” to overcome the added force of gravity acting on the components. The key feature of the two structural extremes above is the *discontinuity* of one of the structural force networks.

J. David Van Horn (scientist, educator), 5110 Rockhill Road, Department of Chemistry, University of Missouri, Kansas City, MO 64110, U.S.A.  
Email: vanhornj@umkc.edu.

Dayu Wang (scientist, educator), 5110 Rockhill Road, Department of Chemistry, University of Missouri, Kansas City, MO 64110, U.S.A.  
Email: dayuwang@mail.umkc.edu.

See <https://direct.mit.edu/leon/issue/54/6> for supplemental files associated with this issue.



**Fig. 1.** Structures (under gravity) considered on a triangle with limiting structures related to extremes in compression and tension (C/T) elements and their continuity. (© J. David Van Horn)

Structures consisting of *both* continuous tension and compression element networks are harder to visualize and exemplify. Many objects—for instance, a sphere, a ring, a box, etc.—probably exhibit combined continuous tensile and compressive forces, and derivative structures may have continuous parts but be constructed with discontinuities at the interfaces of the parts. A geodesic hemisphere may serve as an example (Fig. 1): This object may be engineered to retain its shape in any placement, orientation or gravitational environment via continuous C/T elements. On Earth, in normal usage, this type of structure transmits a continuous compressive force through the structure to the ground or base.

Compressive forces in structures and building methods have predominated humanity's historic approach to architecture; large architectural *tension* elements are more recently utilized. For instance, utilitarian structures that include tension elements such as prestressed concrete, large awnings, cable-stayed construction, suspension bridges and so on started to be notable features in the human landscape over the last century. In contrast, a zero-gravity environment would seem to necessitate the use of tension elements *foremost*, to keep structural components together. A more systematic analysis of structure, examining varying degrees of C/T elements, should be fruitful and underscores the significance

of the discovery of discontinuous compression structures in the mid-twentieth century and their development by Kenneth Snelson and others.

### SOME BACKGROUND ON CHEMICAL BONDING

To relate architectural and artistic structures to molecules requires some reference to the history and concept of chemical bonding—i.e. the forces holding elements together in metals, molecules and materials. The discovery of the electron provided an entry into modern atomic structures of elements and molecular combinations. Useful molecular theories of the early twentieth century (Table 1) described atomic kernels held together by shared electrons for *covalent* structures or composed of electrostatic interactions of ions for holding *ionic* structures together [11]. Metals and alloys may be a more “elemental” aggregate, but the concept of metallic bonding, notably free-electron theory [12], was also developed out of classical theory.

The observation of quantum behavior in molecules and the proposal of wave-particle duality in the 1920s shifted the particle theories of molecular structure toward wave-form molecular orbital theory. This direction has led to our current state-of-the-art, computational methods. Despite the success of quantum mechanics, the rather “particle-based” molecular structure theories of Gilbert Lewis [13], Irving Langmuir [14] and others persist because of their conceptual utility in understanding basic molecular structure and reactivity. Lewis dot structures are taught to students as a starting point for understanding covalent and ionic molecular structures and reactions. This conceptual thread of understanding molecules as particle-based systems was supplemented by the development of valence shell electron pair repulsion (VSEPR) theory and other ideas and constructs [15–18], in parallel with molecular orbital theory.

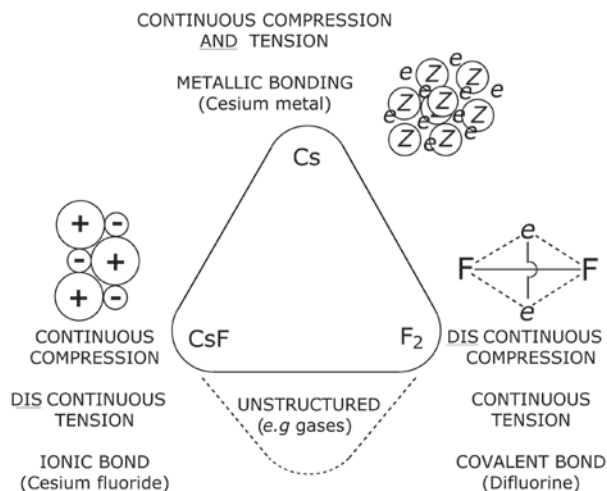
### A COMPRESSION/TENSION MOLECULAR ANALOGY

Considering macroscopic structure in terms of C/T forces, and applying this to metallic, ionic and covalent bonding, led us to make models of chemical interactions consisting of a spectrum of continuous to discontinuous repulsive (compressive, C) and attractive (tensile, T) forces (Table 1; Fig. 2). First, ionic bonding is analogous to a structure with

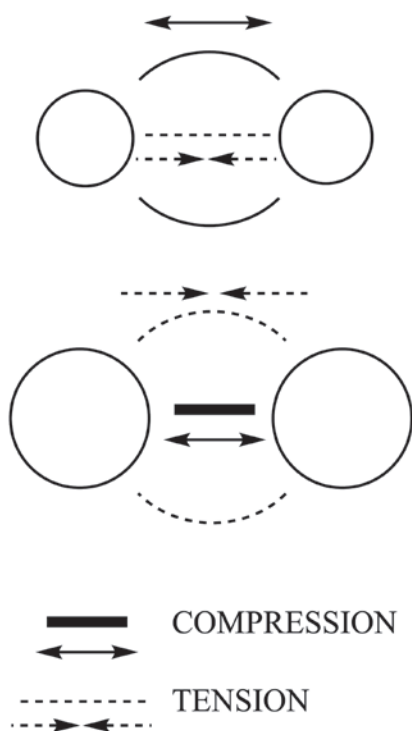
**TABLE 1. Comparison of C/T Structural Types and Molecular Analogs**

Type	First Description	Compression	Tension	Example	Molecular Analog	Bonding Model
1	Ancient	Continuous	<i>Discontinuous</i>	Stone pyramid	Ionic bonding	Berzelius to Kossel (1800–1900)
2	Ancient	Continuous	Continuous	Simple arch	Metallic bonding	Drude (ca. 1900)
3	ca. 1950 (Snelson; Koleychuk)	<i>Discontinuous</i>	Continuous	A tensegrity sculpture	Covalent Bonding	Lewis (ca. 1916), Linnett (1955)
4	Ancient or historic	<i>Discontinuous</i>	<i>Discontinuous</i>	No structure	Gases (cf. <i>χάος</i> to “gas”)	Van Helmont (ca. 1600)

Continuous: unified network of interactions. *Discontinuous*: separated elements or networks of interactions.



**Fig. 2.** A correlation of the three chemical bonding types (metallic, ionic and covalent) to compression and tension elements and networks on a van Arkel-Ketelaar triangle of bonding. (© J. David Van Horn)



**Fig. 3.** Schematics and examples, respectively, of objects made up of two "particles" and C/T force components exhibiting a "simplest tensegrity" (see notes 5 and 20). Compression as lines (-) and tension as dashes (- -). (© J. David Van Horn)

continuous compression elements but *discontinuous* tensile elements (e.g. salts; cesium fluoride). Next, metallic bonding corresponds to having *both* continuous compressive and tensile elements (e.g. pure metals and alloys; cesium). Finally, covalent bonding is analogous to tensegrity as having discontinuous compressive elements and continuous tension elements (e.g. molecular materials; dihydrogen, difluorine). Sculptures and models of idealized bonding types, here conceptualized as C/T systems, may be constructed to represent stable equilibrium structures for the three types of bonding: ionic, metallic and covalent. Moreover, we propose an analogous van Arkel-Ketelaar bonding triangle [19] (Fig. 2), describe structural units to make up molecular models, and present noteworthy covalent molecules in terms of a "molecular tensegrity."

## THE C/T STRUCTURAL CONCEPT

### Two Particle Interactions and a "Simplest Tensegrity"

To adapt tensegrity to these bonding interactions, consider a new "simplest tensegrity" as a C/T structural unit [20]. This unit is made up of two objects or particles with one (or more) compression elements and one (or more) tension elements interacting in a static equilibrium (Fig. 3). In this article, a solid line (-) represents a compressive (repulsive) force, and a dashed line (- -) the tensile (attractive) force.

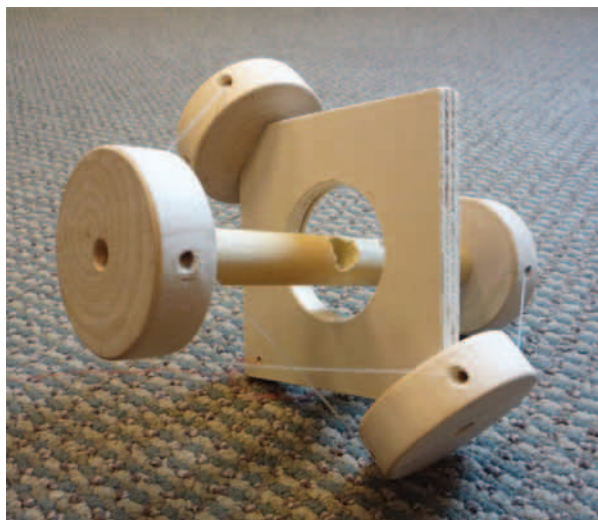
One can make or conceive of many two-body examples. For example, a magnet constrained to float over another identical magnet represents a two-body model, with gravity acting as a tension element against a compressive element—the repulsion between the magnets (Fig. 3, photo and middle schematic). The strength of the magnetic field pushing the magnets apart can be calculated from their mass and size and using appropriate conversion factors (see the appendix in the online supplemental materials). Also illustrated in Fig. 3 (photo and top schematic) is an arrangement of coaxial springs—one in compression, one in tension—making up a "two-particle" simplest tensegrity.

### Dihydrogen and Interpenetrating C/T Elements

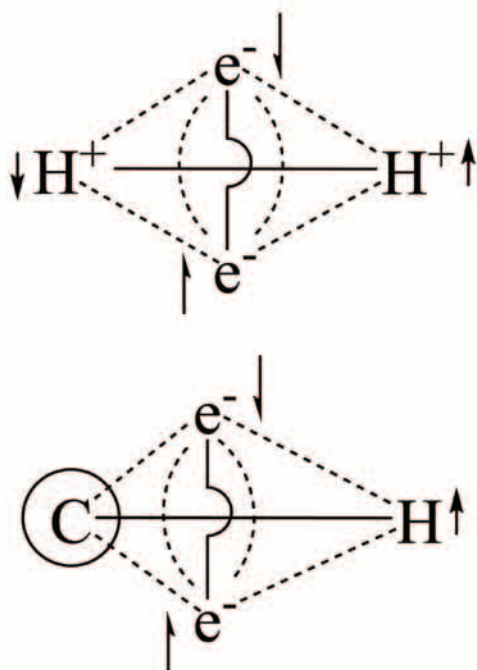
Covalently bonded molecules may be modeled as C/T "tensegrity" systems using combinations of simpler units. Two hydrogen atoms (see the supplemental appendix) are paired to form dihydrogen as follows: The electrons and the protons each separately exhibit repulsion elements while being held together by attractive elements that encompass all four particles (Fig. 4). The attractive interactions in H-H mainly arise from +/- electrostatic charge interactions, but additional stability is attained via tension elements between like particles—electrons in a spin-paired singlet form and protons in a spin-paired arrangement. To follow the stipulation of *discontinuous* compression elements in a tensegrity structure (or here in a covalent bond), we utilize the property of *interpenetrating compression elements*.

### Methine Spar to Methane, Ammonia and Water

From the dihydrogen model, the replacement of hydrogen with other atoms, while retaining the *interpenetrating com-*



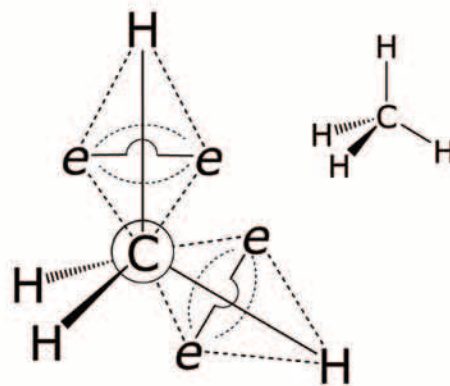
Dihydrogen (H-H)



"Methine Spar" (C-H)

**Fig. 4.** A C/T model for dihydrogen (H-H): Its C/T diagram and that for a C-H "methine spar," including atomic spins, show the various compression and tension elements in the constructs. The model demonstrates *interpenetrating compression elements* (Property 2, Abstract). (©J. David Van Horn)

*pressive elements*, provides additional subunits for making up covalent molecular structures. In this way, one can build a C-H unit, here termed a "methine spar"; additionally, B-H, N-H, O-H and other X-H units will have similar arrangements. The merging of four methine spars provides for the construction of methane ( $\text{CH}_4$ , Fig. 5); likewise, three N-H units plus a nonbonding electron pair lead to ammonia ( $\text{NH}_3$ ) and a pair of O-H spars and two nonbonding electron pairs are merged to form a C/T structure of water ( $\text{H}_2\text{O}$ ). See the online appendix for further elaboration.

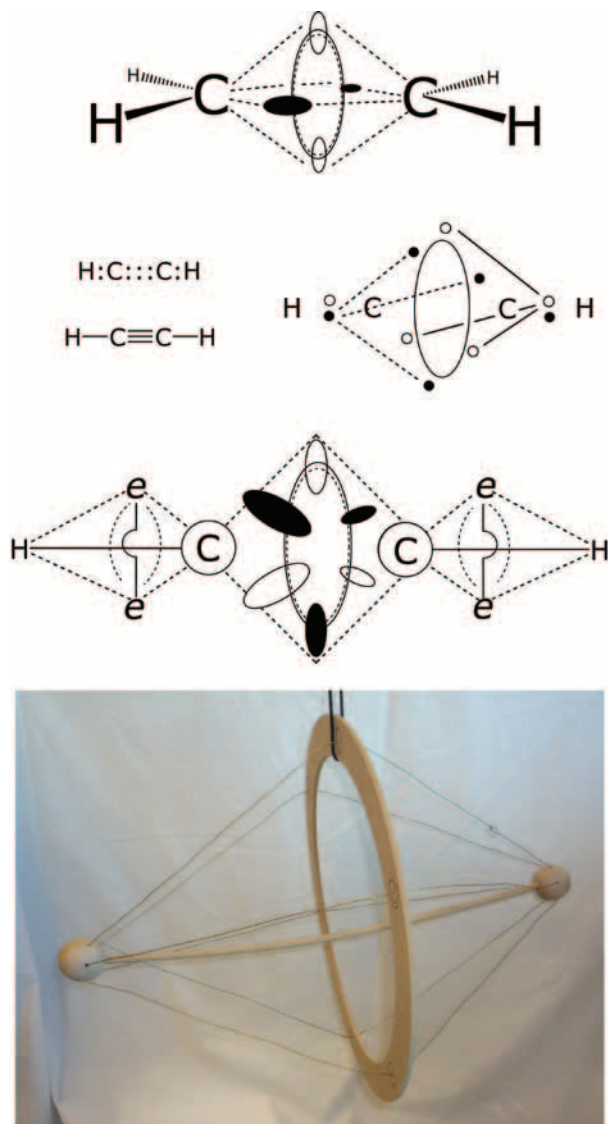


**Fig. 5.** A three-dimensional Lewis structure of methane, and the molecule as a C/T tensegrity; in the sculpture the methine spars have been simplified as hexagonal paddles, but in turn are held to the sphere by a tension network. (© J. David Van Horn)

### Carbon-Carbon Bonds

Singly and multiply bonded atoms can be addressed in the C/T model as follows. For carbon atoms, a carbon-carbon single bond (C-C) is made up of an arrangement like dihydrogen, but with carbon nuclei; a carbon-carbon double bond (C=C) is made up of four electrons over the two atoms, and a triple bond (C≡C), six electrons over the two atoms. We can retain the Lewis drawings of simple molecules, but J.W. Linnett proposed a more detailed picture of the electron arrangements in multiply bonded atoms [21]; his work partially inspired the ideas of C/T systems presented in this article. The C-C single bond and the C=C and C≡C multiple bonds can be built as valid "tensegrity" structures and can be conceptualized as sets of two, four or six electrons providing a tension framework for the stable combination of the carbon atoms (Fig. 6). These constructs may represent a molecular





**Fig. 6.** Lewis dot and Linnett "double-quartet" depictions of acetylene (HCCH) (top, adapted from R.J. Gillespie's work [24]); C/T diagrams of C=C and C≡C bond structures; a tensegrity of Linnett acetylene (bottom) in which the six electrons are considered as a single compression ring. (© J. David Van Horn)

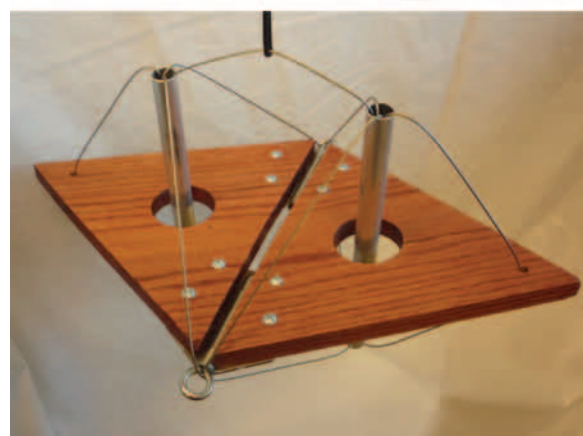
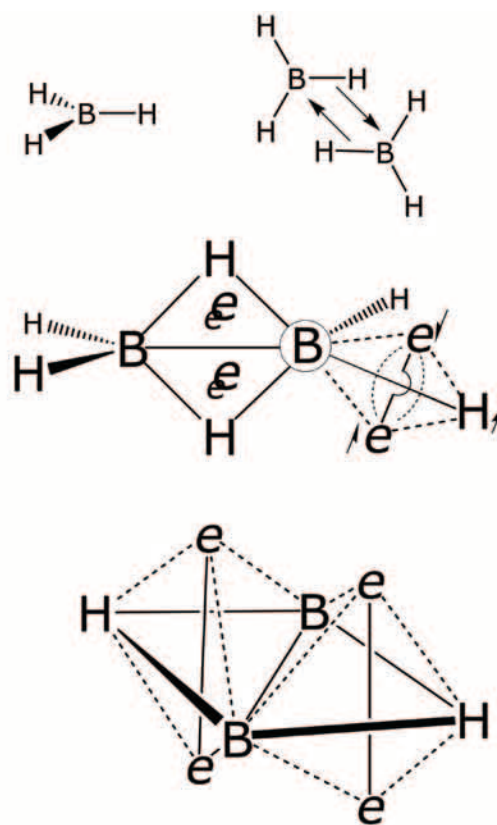
model of structures related to Linnett's "double quartet" theory [22]. Linnett proposed that Lewis's electron "pair" sharing concept was too limited, asserting that "double quartets" or "diamagnetic sets" of electrons account for bonding in C-C, C=C, O-O, F-F and other covalent systems.

Conceptually for basic C/T models, ideal molecular structures only consist of those particles interacting with their nearest neighbors. In reality, particle interactions have a dependence on distance and on the shielding effect of other particles, and they have other dependencies that complicate the exact description of molecular systems. Nevertheless, the idea of a tension network in the C/T molecular concept is additionally useful for understanding possible longer-range interactions within a molecule and allows for effects to be transmitted over considerable distance in a molecule, e.g. the nuclear spin coupling observed in magnetic resonance experiments. In the C/T models as built here, and as known in "tensegrity" sculptures, the individual parts of a structure influence distant parts of a structure.

## Diborane

Boron is an electron-deficient atom, and in borane,  $\text{BH}_3$ , this deficiency is accommodated by the dimerization of two  $\text{BH}_3$  units to form diborane ( $\text{B}_2\text{H}_6$ ). Sharing of electrons from one B-H bond to the adjacent boron atom provides stability in the form of a two-electron, three-center bond. This bonding arrangement is treated by many approaches, including the present C/T concept.

The arrangement of particles in diborane as a C/T structure (Fig. 7) is described by considering the four external B-H bonds to be B-H spars (see above)—a  $2-e^-/2$ -atom unit. The two boron atoms and two central hydrogen atoms are



**Fig. 7.** Borane ( $\text{BH}_3$ ) and diborane ( $\text{B}_2\text{H}_6$ ) chemical drawings with a partial C/T diagram of diborane; detail of the  $[\text{B}_2\text{H}_2]$  C/T core; tensegrity sculpture of the diborane core. (© J. David Van Horn)

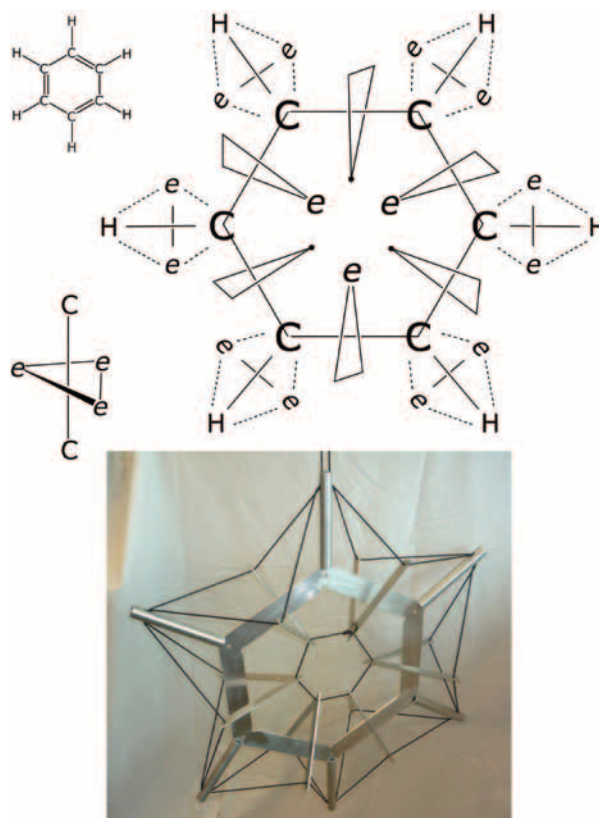
arranged as two triangular compression systems—each a  $2-e/3$ -atom unit. Placement of the four shared bonding electrons above and below the plane of the boron atoms provides tension elements holding the central hydrogen and boron atoms together. In this fashion, all the hydrogen atoms are satisfied with two electrons, and the boron atoms are stabilized with eight electrons (an “octet” in Lewis’s terms, or a “double quartet” in Linnett’s).

### Benzene

A covalent molecule important to this discussion is benzene ( $C_6H_6$ ). The arrangement of atoms in benzene is uniform and symmetric due to the distribution of six pi electrons (their electron density) over the six carbon atoms rather than “localized” as  $C=C$  double bonds. A C/T model of benzene starts with six external methine spars ( $C-H$ ,  $2 e^-$  over 2 atoms). The carbon–carbon bonding arrangement in the ring consists of subunits with three electrons and two carbon atoms ( $3 e^-$  over 2 atoms), with interactions between these units around the inside of the hexagonal ring. This arrangement accounts for the uniform structure of benzene, and its stability, by providing each carbon atom with a preferred “octet” of electrons in suitably “spin-paired” configurations (see Fig. 8). The electrons in the ring are spaced between carbon atoms rather than colinear with the  $C-H$  spar, giving an eight-electron arrangement for each carbon and a stable ring of six electrons inside the ring, including an acceptable spin pairing. A tensegrity model—employing trigonal compression units for the ring electrons, spars for  $C-H$  components, and a hexagonal compression unit for the carbon atom ring—illustrates viable C/T properties applied to benzene (Fig. 8). This benzene tensegrity is directly analogous to Linnett’s theoretical structure for benzene [23].

### CONCLUSION

Here, we reevaluate structure in terms of compression (repulsion) and tension (attraction) force elements. By analogy and using Snelson’s descriptions, we model molecular bonding as networks of differing continuous or discontinuous C/T elements. We model covalent molecular structures (especially related to Linnett’s descriptions) as tensegrities and approach a purely *discontinuous* compression/*continuous* tension structure. Specifically, tensegrity structure provides



**Fig. 8.** Diagrams of the Lewis structure of benzene ( $C_6H_6$ ), a 3-electron/2-carbon C/T structural unit, and benzene as a tensegrity. In the benzene tensegrity the carbon ring and electron triplet compression units have been simplified as hexagon and open triangles, respectively, and the methine spars as rods. (© J. David Van Horn)

a molecular model for Linnett’s structural approach. The key aspects of a molecular tensegrity and derivative artistic structures include (1) taking two particle interactions as a simplest unit and (2) the use of interpenetrating, but *not* necessarily interacting, compression units (or tension units). For artists, architects and engineers, the classification of structure and elements and the C/T models here may offer direction for creating new works or for the study of old. For scientists, the consideration of particle-based structures as C/T systems offers new analogies of the microscopic universe.

### Acknowledgments

This article is written in memory of Kenneth Snelson for his structural discovery and for his production and description of tensegrity sculpture. We thank Jami Wade for completing a history of bonding project and Charles Smith for assisting in model building with a grant from the University of Missouri, Kansas City undergraduate SEARCH program. Architect Ted Seligson (Fellow, AIA; UMKC Architecture+Urban Planning and Design) greatly encouraged our investigations of tensegrity structures.

### References and Notes

- 1 C.S. Smith, “Metallurgy as a Human Experience,” *Metallurgical Transactions A* **6A** (1975) pp. 603–623.
- 2 C.S. Smith, *From Art to Science: Seventy-Two Objects Illustrating the Nature of Discovery* (Cambridge, MA: MIT Press, 1980).
- 3 A. Deplazes, ed., *Constructing Architecture. Materials, Processes, Structures*, G.H. Söffker, trans. (Birkhäuser: Basel, 2008).
- 4 A. Pugh, *An Introduction to Tensegrity* (Berkeley: University of California Press, 1976).

- 5 H. Kenner, *Geodesic Math* (Berkeley: University of California Press, 1976).
- 6 Pugh [4].
- 7 K. Snelson, "The Art of Tensegrity," *International Journal of Space Structures* **27** (2012) pp. 71–80.
- 8 V.F. Koleychuk, V. Polyakoff and V. Chudnovsky, "The Evolution of My Kinetic Work," *Leonardo* **27**, No. 5, 395–398 (1994); V.F. Koleychuk, "The Dvizheniye Group: Toward a Synthetic Kinetic Art," *Leonardo* **27**, No. 5, 433–436 (1994).
- 9 K. Snelson, *X-Piece*, sculpture, 1948; K. Snelson, "An Artist's Atom," *Leonardo* **27**, No. 3, 231–236 (1994); K. Snelson, "Art and Ideas" online publication (2013): [www.kennethsnelson.net/KennethSnelson\\_Art\\_And\\_Ideas.pdf](http://www.kennethsnelson.net/KennethSnelson_Art_And_Ideas.pdf).
- 10 R. Motro, *Tensegrity: Structural Systems for the Future* (London: Kogan Page Science, 2003); D.E. Ingber, "The Architecture of Life," *Scientific American* **278**, No. 1, 48–57 (1998)
- 11 L. Pauling, *The Nature of the Chemical Bond* (Ithaca: Cornell Univ. Press, 1967).
- 12 A. Sommerfeld, "An Electron Theory of Metals from Fermi Statistics," *Zeitschrift für Physik* **47** (1928) pp. 1–3.
- 13 G.N. Lewis, "The Atom and the Molecule," *Journal of the American Chemical Society* **38** (1916) pp. 762–785.
- 14 I. Langmuir, "The Arrangement of Electrons in Atoms and Molecules," *Journal of the American Chemical Society* **41** (1919) pp. 868–934.
- 15 R.J. Gillespie, "The Valence-Shell Electron-Pair Repulsion (VSEPR) Theory of Directed Valency," *Journal of Chemical Education* **40** (1963) pp. 295–301.
- 16 R.J. Gillespie, "Fifty Years of the VSEPR Model," *Coordination Chemistry Reviews* **252** (2008) pp. 1315–1327.
- 17 J.W. Linnett, *The Electronic Structure of Molecules: A New Approach* (London: Methuen & Co, 1964).
- 18 J.W. Linnett, "A Modification of the Lewis-Langmuir Octet Rule," *Journal of the American Chemical Society* **83** (1961) pp. 2643–2653.
- 19 W.B. Jensen, "A Quantitative van Arkel Diagram," *Journal of Chemical Education* **72** (1995) pp. 395–398.
- 20 Compare this "simplest" system with Kenner [5], who relates the simplest tensegrity structure consisting of three compressive elements in a tension network—the classic tensegrity prism (Fig. 1).
- 21 Linnett [17].
- 22 Linnett [18].
- 23 Linnett [17].
- 24 Gillespie [15].

---

Manuscript received 13 March 2020.

**J. DAVID VAN HORN** is associate professor of chemistry at the University of Missouri, Kansas City. The ideas and structures of a molecular tensegrity grew out of considering the question, "What is a covalent bond?"; interacting with architecture students; and teaching courses, including structure and bonding concepts, from 2007 to present.

**DAYU WANG** joined the Department of Chemistry at the University of Missouri, Kansas City to pursue an interdisciplinary doctoral degree in chemistry and physics. His dissertation research work focused on bonding theory and mathematical and computational analysis of microscopic interactions between particles at molecular and atomic levels. He currently teaches at St. Charles Community College, Cottleville, Missouri.