

# Transforming Optimal Tetrahelices between the Boerdijk-Coxeter Helix and a Planar-faced Tetrahelix

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The Boerdijk-Coxeter helix (BC helix, or tetrahelix) is a face-to-face stack of regular tetrahedra forming a helical column. Treating the edges of these tetrahedra as structural members creates an attractive and inherently rigid space frame, and therefore is interesting to architects, mechanical engineers, and roboticists. A formula is developed that matches the visually apparent helices forming the outer rails of the BC helix. This formula is generalized to a formula convenient to designers. Formulae for computing the parameters that give proven edge-length minimax-optimal tetrahelices are given, allowing transformation through a continuum of optimum tetrahelices of varying curvature while maximizing regularity. The endpoints of this continuum are the BC helix and a structure of zero curvature, the *equitetrabeam*. Only one out of three members in the system change their length to transform the structure into any point in the continuum. Numerically finding the rail angle from the equation for pitch allows optimal tetrahelices of any pitch to be designed. An interactive tool for such design and experimentation is provided: <https://pubinv.github.io/tetrahelix/>. A formula for the inradius of optimal tetrahelices is given. The continuum allows a regular Tetrobot supporting a length change of less than 16% in the BC configuration to untwist into a hexapodal or  $n$ -podal robot to use standard gaits.

## 1 Introduction

The Boerdijk-Coxeter helix [1] (BC helix) (see figs. 1 and 2), is a face-to-face stack of tetrahedra that winds about a straight axis. Architects, structural engineers, and roboticists are inspired by and follow such regular mathematical models. However, since they can also build structures and machines from members of differing or even dynamically changing length, it is useful to develop the mathematics of structures formed from tetrahedra where one relaxes regularity.

The vertices of the tetrahedra lie upon three helices about the central axis. The Tetrobot [2, 3] uses the regularity of this geometry to make a tentacle-like robot that can crawl

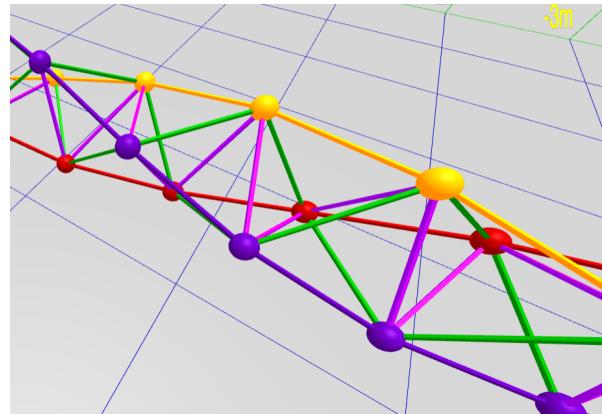


Fig. 1. BC Helix Close-up (partly along axis)

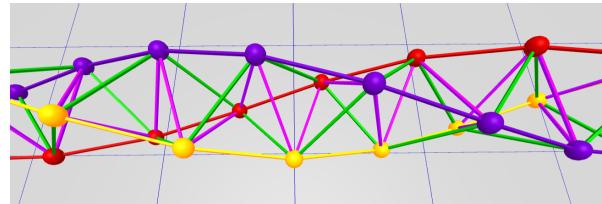


Fig. 2. BC Helix Close-up (orthogonal)

like a mollusk. These modular robotic systems use mechanical actuators which can change their length, connected by special joints, such as the 3D printable Song-Kwon-Kim [4] joint or the CMS joint [5] used in the original Tetrobot. This allows many members to meet in a single point. Such machines can follow purely regular mathematical models such as the Boerdijk-Coxeter helix or the octet truss [6].

Buckminster Fuller called the BC helix a *tetrahelix* [7], a term now commonly used. This paper reserves *BC helix* to mean the purely regular structure and use *tetrahelix* to refer to any structure isomorphic to the BC helix.

Imagining fig. 1 or fig. 2 as a static mechanical structure, observe that it is useful to the mechanical engineer because the structure is a mechanically strong, inherently rigid, omni-

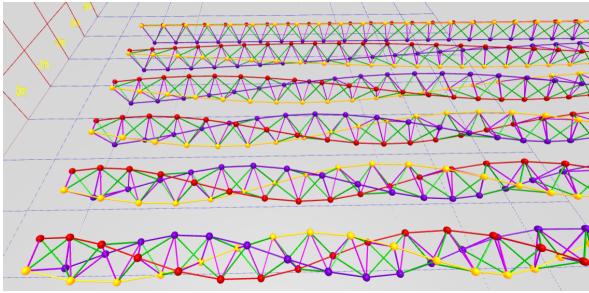


Fig. 3. A Continuum of Tetrahelices

triangulated space frame. Then imagine that each static edge is replaced with an actuator that can dynamically become shorter or longer in response to electronic control, and the vertices are joints that support sufficient angular displacement for this to be possible. An example of such a machine is a Tetrobot, shown in fig. 4 and fig. 5.

A BC helix does not rest stably on a plane. It is convenient to be able to “untwist” it and to form a tetrahelix space frame that has a flat planar surface. By making length changes in a certain way, a *tetrahelix untwists* to form a *tetrabeam* which has planar faces and has, for example, an equilateral triangular profile. This paper develops the equations needed to untwist the tetrahelix. All math developed here is available in JavaScript and demonstrated by an interactive design website <https://pubinv.github.io/tetrahelix/> [8] and a video [9], from which figs. 1 and 2 and later figures in this paper are taken.

Figure 3 displays a continuum of tetrahelices optimal *in the sense of being as regular as possible*, which is the main result of this paper. The closest helix is the BC helix, and the furthest is the equitetrabeam, defined in section 6 and figs. 9 and 10.

Trusses and space frames remain an important design field in mechanical and structural engineering [10], including deployable and moving trusses [11, 12].

### 1.1 Utility for Robotics

Starting twenty years ago, Sanderson [13], Hamlin, [3], Lee [14], and others created a style of robotics based on changing the lengths of members joined at the center of a joint, thereby creating a connection to pure geometry. More recently, NASA has experimented with tensegrities [15, 16], a different point in the same design spectrum. In particular, the tetrahelix is related to the tetraspline [17] concept used as a model of a tensegrity robot. Although tensegrities are not member-for-member isomorphic to the tetrahelix as the tetrobot is, they often use repeated tetrahedral cells, so this work of pure geometry has some applied relevance to them.

As suggested by Buckminster Fuller, the most convenient geometries to consider are those that have regular member lengths, in order to facilitate the inexpensive manufacture and construction of the robot. In a plane, the octet truss [6] is such a geometry, but in a line, the Boerdijk-Coxeter helix is such a regular structure.

However, a robot must move, and so it is interesting to

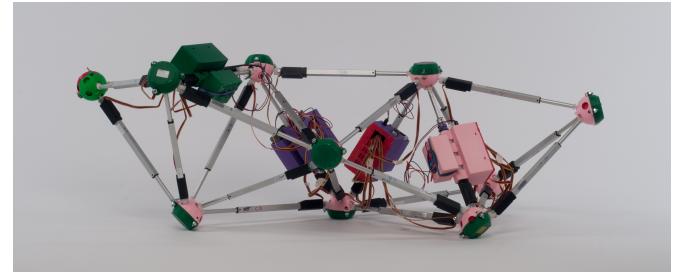


Fig. 4. 7-Tet Tetrobot in relaxed, or BC helix configuration

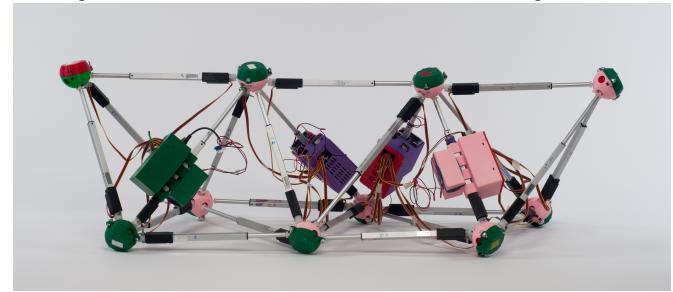


Fig. 5. The Equitetrabeam: Fully Untwisted 7-Tet Tetrobot in Hexapod Configuration

consider the transmutations of these regular geometries. Developing a functional gait for our physical Tetrobot (the 7-Tet Glussbot) was in fact the motivation for this work. By changing only the length of only one third of the members, one can dynamically untwist a physical Tetrobot forming the Boerdijk-Coxeter configuration into the equitetrabeam which rests flat on the plane, as shown in figs. 4 and 5.

By untwisting the tetrahelix so that it has a planar surface resting on the ground, each vertex touching the ground becomes a foot or pseudopod. A robot can thus become a hexapod or  $n$ -pod Tetrobot, and the already well-developed approaches to hexapod gaits may be applied to make the robot walk or crawl.

### 1.2 Summary of Results

The remainder of this paper:

- provides a new formulation for the BC helix that is more natural for engineers,
- defines a concept of minimum maximum edge-length optimality that maintains the structure as close to regularity as possible,
- proves that all optimal tetrahelices are in fact triple helices,
- provides formulae for constructing optimal tetrahelices of different twists or for optimally transforming a robot from a twisted to a planar configuration in a way that maintains optimum regularity,
- gives a formula for the inradius of an optimal tetrahelix,
- describes a completely planar tetrahelix (*the equitetrabeam*) useful as a structural beam or for applying standard robot gaits to a tetrahedral robot, and
- discusses the continuum of optimal tetrahelices between the BC helix and equitetrabeam.

## 2 A Designer's Formulation of the BC Helix

Engineers would like to design nearly regular tetrahedra with a formula that gives the vertices in space. Ideally, this would be done by choosing the lengths of a small set of members. In a space frame, this is a static design choice; in a Tetrobot, it is a dynamic choice that can be used to twist the robot and/or exert linear or angular force on the environment.

Ideally, a simple formula would define the vertices based on any curvature or pitch we choose. It is a goal of this paper to relate the Cartesian coordinate approach and the member-length approach to generating a tetrahelix continuum.

H.S.M. Coxeter constructs the BC helix [1] as a repeated rotation and translation of the tetrahedra by showing the rotation is:

$$\theta_{bc} = \arccos(-2/3) \quad (1)$$

and the translation:

$$h_{bc} = 1/\sqrt{10}. \quad (2)$$

Note that  $\theta_{bc}$  is approximately  $0.37 \cdot 2\pi$  radians or 131.81 degrees. The angle  $\theta_{bc}$  is the rotation of each tetrahedron, not the tetrahedra along a rail. In fig. 1, each tetrahedron has either a yellow, blue, or red outer edge or rail. That is, a blue-rail tetrahedron is rotated slightly more than a  $1/3$  of a revolution to match the face of the yellow tetrahedron.

R.W. Gray's website [18], repeating a formula by Coxeter [1] in a more accessible form, gives the Cartesian coordinates

$\begin{bmatrix} x \\ y \\ z \end{bmatrix}$  for a counter-clockwise BC helix in a right-handed coordinate system:

$$\mathbf{V}(n) = \begin{bmatrix} r_{bc} \cos n\theta_{bc} \\ r_{bc} \sin n\theta_{bc} \\ nh_{bc} \end{bmatrix}, \quad (3)$$

$$\text{where: } \begin{aligned} r_{bc} &= \frac{3\sqrt{3}}{10} \approx 0.5196, \\ h_{bc} &= 1/\sqrt{10} \approx 0.3162, \text{ and} \\ \theta_{bc} &= \arccos(-2/3), \end{aligned}$$

and  $n$  represents each integer numbered vertex in succession on the  $z$ -axis.

The apparent rotation of a vertex on an outer-edge, that is  $\mathbf{V}(n)$  relative from  $\mathbf{V}(n+3)$  for any integer  $n$  in eq. (3), is  $3\theta_{bc} - 2\pi$ .

This formula defines a helix, but it is not any of the apparent helices, or *rail* helices, of the BC helix, but rather one that winds much more rapidly through all vertices. To a designer of tetrahelices, it is more natural to think of the three helices which are visually apparent, that is, those three which are closely approximated by the outer edges or rails of the BC helix. Think of each of these three rails as being a different color: red, blue, or yellow. This situation is illustrated in fig. 6, wherein the black helix represents that generated

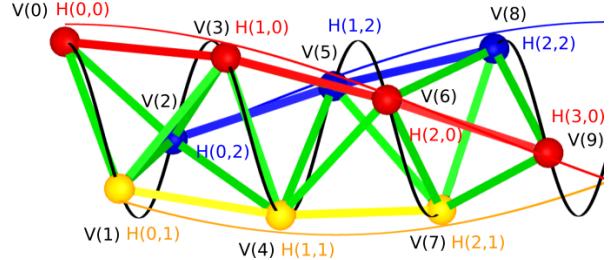


Fig. 6. Rail helices (H) vs. Coxeter/Gray helix (V)

by eq. (3), and the colored helices are generated by eq. (4), below.

In order to develop the continuum of slightly irregular tetrahelices, a formula is needed that gives us the vertices of just one rail helix, denoted by color  $c$  and integer vertex number  $n$ :

$$(\forall n \in \mathbb{Z}, \forall c \in \{0, 1, 2\} : \mathbf{H}_{BCcolored}(n, c) = \mathbf{V}(3n + c)).$$

Such a helix can be written:

$$\mathbf{H}_{BCcolored}(n, c) = \begin{bmatrix} r_{bc} \cos((3\theta_{bc} - 2\pi)n + c\theta_{bc}) \\ r_{bc} \sin((3\theta_{bc} - 2\pi)n + c\theta_{bc}) \\ 3h_{bc}(n + c/3) \end{bmatrix}, \quad (4)$$

$$r_{bc} = \frac{3\sqrt{3}}{10},$$

$$\text{where: } h_{bc} = 1/\sqrt{10}, \text{ and}$$

$$\theta_{bc} = \arccos(-2/3).$$

In this formula, integer values of  $n$  may be taken as a vertex number for one rail and used to compute its Cartesian coordinates. Allowing  $n$  to take non-integer values defines a continuous helix in space which is close to the segmented polyline of the outer tetrahedra edges, and equals them at integer values.

Figure 6 illustrates this difference with a 7-tetrahedra BC helix, which is in fact the same geometry as the robot illustrated in fig. 5. Although the vertices coincide, eq. (3) evaluated at real values generates the black helix which runs through every vertex, and eq. (4) defines the red, yellow, and blue helices. In this figure, these continuous rail helices have been rendered at a slightly higher radius than the vertices for clarity; in actuality, the maximum distance between the continuous, curved helix and the straight edges between vertices is much smaller than can be clearly rendered.

The quantity  $(3\theta_{bc} - 2\pi) \approx 35.43^\circ$  is the angular shift between adjacent vertices on the same rail:  $\mathbf{V}(3n + c) = \mathbf{H}_{BCcolored}(n, c)$  and  $\mathbf{V}(3(n+1) + c) = \mathbf{H}_{BCcolored}(n+1, c)$ . This quantity appears so often that we call it the "rail angle,  $\rho$ ". For the BC helix,  $\rho_{bc} = (3\theta_{bc} - 2\pi)$ .

Note, in fig. 7, the  $z$ -axis travel for one rail edge is denoted by  $d$ . In eq. (3) and eq. (4), the variable  $h$  is used for one third of the distance we name  $d$ . The fact that  $d = 3h$  is justified later. In this paper, we assume the length of a rail is always 1 as a simplification, except in proofs concerning rail length. The rail length is a parameter in the JavaScript code

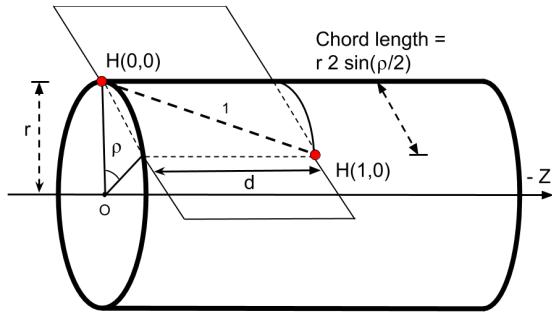


Fig. 7. Rail Angle Geometry

in [https://github.com/PubInv/tetrahelix/blob/master/js/tetrahelix\\_math.js](https://github.com/PubInv/tetrahelix/blob/master/js/tetrahelix_math.js) [8].

The  $\mathbf{H}_{BCcolored}(n, c)$  formulation can be further clarified by rewriting directly in terms of the rail angle  $\rho_{bc}$  rather than  $\theta_{bc}$ . Intuitively, an expression where  $c/3$  is multiplied by a  $1/3$  rotation plus the rail angle  $\rho$  is sought. We expand the expressions  $\theta_{bc}$  and  $\rho_{bc}$  in eq. (4) and seek to isolate the term  $c2\pi/3$ .

Thus, starting with the expression:

$$c\theta_{bc}$$

introduce 3 into the denominator...

$$(c/3)(3\theta_{bc})$$

seeking  $2\pi$  in the numerator, add canceling terms...

$$(c/3)((3\theta_{bc} - 2\pi) + 2\pi)$$

...and then use the definition of  $\rho_{bc}$

$$(c/3)\rho_{bc} + c2\pi/3$$

to finally obtain:

$$c(\rho_{bc} + 2\pi)/3. \quad (5)$$

This allows eq. (4) to be rewritten:

$$\mathbf{H}_{BCcolored}(n, c) = \begin{bmatrix} r\cos\rho_{bc}n + c(\rho_{bc} + 2\pi)/3 \\ r\sin\rho_{bc}n + c(\rho_{bc} + 2\pi)/3 \\ (n + c/3)h_{bc} \end{bmatrix}, \quad (6)$$

where:  $\rho_{bc} = (3\theta_{bc} - 2\pi)$ , and  $h_{bc} = 1/\sqrt{10}$ .

Recall that  $c \in \{0, 1, 2\}$ , but  $n$  is continuous (rational or real-valued). It can now be asserted that in fig. 6 the black helix winds at  $\frac{3\theta_{bc}}{\rho_{bc}} \approx 11.16$  times the rate of a rail helix.

From this formulation it is easy to see that moving one vertex on a rail ( $\mathbf{H}_{BCcolored}(n, c)$ ) to  $\mathbf{H}_{BCcolored}(n + 1, c)$  for any  $n$  and  $c$ ) moves us  $\rho_{bc}$  radians around a circle. Since:  $\frac{2\pi}{\rho_{bc}} \approx 10.16$  there are approximately 10.16 red, blue or yellow tetrahedra on one rail in a complete revolution of the tetrahelix.

The pitch of any tetrahelix, defined as the axial length of a complete revolution where  $\rho \neq 0$  is:

$$p(\rho) = \frac{2\pi d}{\rho}. \quad (7)$$

The pitch of the Boerdijk-Coxeter helix of edge length 1 is the length of three tetrahedra times  $p(\rho_{bc})$ :

$$\frac{3h_{bc}2\pi}{\rho_{bc}} = \frac{6\pi}{\sqrt{10}\rho_{bc}} \approx 9.64. \quad (8)$$

The pitch is less than the number of tetrahedra because the tetrahedra edges are not parallel to the axis of the tetrahelix. It is a famous and interesting result that the pitch is irrational. A BC helix never has two tetrahedra at precisely the same orientation around the  $z$ -axis. However, this is inconvenient to designers, who might prefer a rational pitch. The idea of developing a rational period by arranging solid tetrahedra by relaxing the face-to-face matching has been explored [19]. The next sections develop slightly irregular edge lengths that support, for example, a pitch of precisely 12 tetrahedra in one revolution which would allow an architect to design a pleasing column having the top and bottom tetrahedra in the same relationship to the viewer on both the capital and the basis.

### 3 Optimal Tetrahelices are Triple Helices

As engineers and roboticists it is desirable to design tetrahelices that are slightly irregular that “untwist” the BC helix in an optimal way. For machines made out of linear actuators with limited range of extension, the best definition of optimality is to minimize the difference in lengths between the shortest and longest members in the robot of a given radius. By maintaining all lengths as close to the same “regular” length as possible, such as the mean length of the actuator, one retains the greatest possible freedom of motion for the robot.

This paper use the term *tetrahelix* to mean any structure physically constructible of vertices and finite edges which is isomorphic to the BC helix, but with possibly different edge lengths, and in which the vertices lie on three helices (red, blue, and yellow, or  $(R, B, Y)$ ). Mathematically, this structure extends without bound, although physical robots or variable geometry trusses will be truncations of such a structure. This idea is captured by a function  $T$  that gives the length between

any two nodes that are connected, and undefined ( $\perp$ ) when not connected :  $T(n_1, n_2) : \mathbb{Z} \times \mathbb{Z} \mapsto \mathbb{R} \cup \{\perp\}$ . To describe a physically realizable machine, the function  $T$  representing a tetrahelix is constrained:  $(\forall n_1, n_2 : T(n_1, n_2) > 0)$ . For a BC helix,  $(\forall x, y : T(x, y) \neq \perp \Rightarrow T(x, y) = 1)$ .

The ratio of the longest member in a testrahelix to the shortest is:

$$R(T) = \frac{\max\{T(n_1, n_2) | n_1, n_2 \in \mathbb{Z}\}}{\min\{T(n_1, n_2) | n_1, n_2 \in \mathbb{Z}\}} \quad (9)$$

The ratio of the BC helix is 1:  $R(H_{BC}) = 1$ . A *triple helix* is three congruent helices that share an axis. The remainder of this section proves that optimal tetrahelices are in fact triple helices. In stages, this section proves that the helices in optimal tetrahelices:

1. have the same pitch,
2. have parallel axes,
3. share the same axis,
4. have the same radius,
5. have the same rail length,
6. have axially equidistant vertices, and therefore
7. are in fact triple helices.

The formula for radius that optimizes the tetrahelix for a given rail angle is the result of the section 4.

**Theorem 1.** All three helices in any physically realizable tetrahelix have the same pitch and parallel axes.

*Proof.* Suppose that all three rails do not have the same pitch. Let  $n_1$  be a node on a shortest edge between two rails. Let  $n_2$  be a node on a different rail. Increasing the difference  $\|n_2 - n_1\|$  increases edge lengths  $T(n_1, n_2)$  without bound, which is not physically realizable.

Similarly, if the axes are not parallel, for any length  $\lambda$  there is an edge of  $T(x, y)$  such that  $T(x, y) > \lambda$ , which is not physical.

Theorem 1 justifies talking about the singular *pitch* of the optimal tetrahelix as the pitch of its three rail helices ( $R, B, Y$ ), even though there are three such helices of equivalent pitch. Since the axes of helices of any physical tetrahelix are parallel, take them to be parallel to the  $z$  axis. Define the radius of the tetrahelix:

$rad(T)$  = the radius of the smallest cylinder  
which contains all of nodes of the tetrahelix  $T$

Define a *minimax edge-length optimal tetrahelix* or just an *optimal tetrahelix* to be a tetrahelix for which there exists no other tetrahelix of the same radius with lower ratio of longest edge length to shortest edge length

$$OPT(T) \equiv \neg(\exists S : R(S) < R(T) \wedge rad(S) = rad(T)) \quad (10)$$

**Lemma 1.** A tetrahelix where all points lie on the same line is not optimal.

*Proof.* As a little lemma for the proof below, observe that a tetrahelix  $T$  of zero radius, where all points lie on the same line, is not as optimal as a tetrahelix of a small radius. The edges between rails ( $R, B, Y$ ) will be shorter than the rail edges, and moving them apart slightly to form  $T'$  lengthens the between-edge rails, improving the ratios, so  $R(T') < R(T)$ .

In the proof, below, it is useful to consider projection diagrams that are the axial projection of a tetrahelix onto the  $XY$ -plane. Figures 8 and 13 are examples of such a diagram.

**Lemma 2.** If the rail angle  $0 < \rho < \pi$  is a rational multiple of  $\pi$ , then the projection of edges in a helix of that rail angle along the  $z$ -axis onto the  $XY$ -plane form a regular polygon of 3 or more sides, otherwise they fill in a complete circle.

*Proof.* All points lying on a helix projected along the axis lie on a circle in the  $XY$ -plane. (By lemma 1, the circle is not a simple point.) Helices are periodic in the  $z$  dimension modulo  $2\pi$ . If  $2\pi/\rho$  is irrational, the projection onto the  $XY$ -plane will contain an unbounded number of points on a circle. If and only if  $2\pi/\rho$  is rational, the projection onto the  $XY$ -plane will contain a finite number of points. Because  $\pi$  is transcendental and irrational,  $2\pi/\rho$  is rational if and only if  $\rho = a\pi/b$ , where  $a$  and  $b$  are integers and, assume without loss of generality,  $a$  and  $b$  are coprime. Since  $\rho < \pi$ , therefore  $a < b$ . Also,  $\rho > 0$ , therefore  $a > 0$ . The number of points in the projection is  $2b$  if  $a$  is odd, and  $b$  if  $a$  is even. This polygon has at least 3 sides, since either  $\rho$  is irrational or  $b > a$ , and therefore  $b \geq 2$ . If  $a/b = 1/2$ , the projection is a square, which has four sides.

**Theorem 2.** Any optimal tetrahelix with a rail angle of magnitude less than  $\pi$  has all three axes coincident.

*Proof.* Case 1: Suppose that  $\rho$  is zero. Each helix has zero curvature, that is, it is a straight line. These lines are equivalent to some three degenerate helices with coincident axes, possibly with different radii, so long as there is a phase term in the defintion of the helix, as in eq. (4). That the radii must be equivalent is shown later.

Case 2: Suppose that  $\rho$  is positive but less than  $\pi$ . In this case, each rail helix has curvature. The projection of points in the  $XY$  plane creates a figure guaranteed to have points on either side of any line through the axis of such a helix, because the figure is either an  $n$ -gon or a circle by lemma 2.

By symmetry without loss of generality, define the Red helix to have its axis on the  $z$ -axis. Since there must be at least one Red-to-Yellow or a Red-to-Blue edge that is either a minimum or a maximum, without loss of generality, define the Blue helix to be a helix that has an edge connection to the Red helix that is either a maximum or a minimum. Let  $B'$  be a translation in the  $XY$ -plane of the blue helix  $B$  so that its

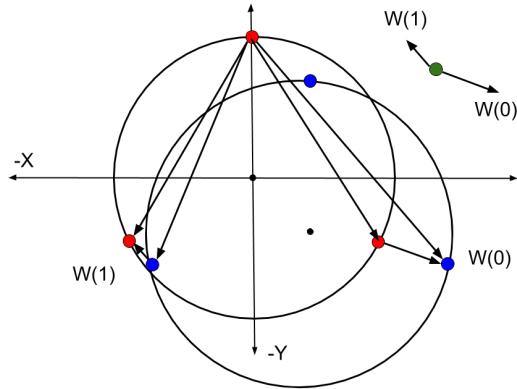


Fig. 8. Wobble Vectors from Non-Coincident Axes

axis is the  $z$ -axis and coincident with the red helix  $R$ . Let  $D$  be the distance between the axis of the Blue helix  $B$  and  $B'$ . We will show that if  $D > 0$  then  $B$  “wobbles” in a way that cannot be optimal. Define a wobble vector by:

$$\mathbf{W}(n) = \mathbf{B}(n) - \mathbf{B}'(n). \quad (11)$$

where  $\mathbf{B}(n)$  and  $\mathbf{B}'(n)$  is the vector  $\begin{bmatrix} x \\ y \end{bmatrix}$  for the projection of the  $n$ th vertex of  $B$  and  $B'$ . Note that  $\|\mathbf{R}(n) - \mathbf{B}'(n+k)\|$  (the Euclidean distance of the vertices) is a constant for any  $k$ , because  $R$  and  $B'$  have the same pitch and the same axis, even if they do not have the same radius.

Figure 8 illustrates this situation. The diagram represents the projection along the  $z$ -axis of a few points into the  $XY$ -plane.

Since  $\rho < \pi$  by assumption, by lemma 2, the set of wobblies  $\{\mathbf{W}(n)|\text{for any } n\}$  contains at least three vectors, at least two of which point in different directions. For any point not at the origin, at least one of these vectors moves closer to the point and at least one moves further away.

The set of all lengths in the tetrahelix is a superset of:  $L = \{\|\mathbf{R}(n) - \mathbf{B}(n)\|\}$ , which, by our choice, has at least one longest or shortest length.  $L = \{\|\mathbf{R}(n) - (\mathbf{B}'(n) + \mathbf{W}(n))\|\}$  and so  $L = \{\|(\mathbf{R}(n) - \mathbf{B}'(n)) - \mathbf{W}(n)\|\}$ . But  $\mathbf{R}(n) - \mathbf{B}'(n)$  is a constant, so the minimax value of  $L$  is improved as  $\|\mathbf{W}(n)\|$  decreases. By our choice that there is a Blue-to-Red edge that is either a maximum or a minimum, this improves the minimax value of the total tetrahelix.

This process can be carried out on both the Blue and Yellow helices (perhaps simultaneously) until  $\mathbf{W}(n)$  is zero for both, finding a tetrahelix of improved overall minimax value at each step. So a tetrahelix is optimal only when  $\mathbf{W}(n) = 0$ , and therefore when  $D = 0$  and  $\mathbf{B}(n) = \mathbf{B}'(n)$ , and all three axes are coincident.

Now that it is proven that the axes are coincident and parallel and that the pitches are the same for all helices, any optimum tetrahelix can be generated with a simple equation

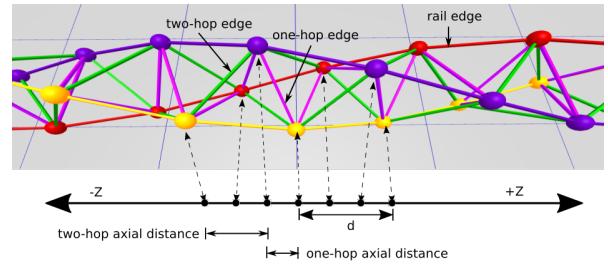


Fig. 9. Edge Naming

for helices:

$$\mathbf{V}_{\text{triple}}(n, c) = \begin{bmatrix} r_c \cos(n\alpha + c2\pi/3 + \phi_c) \\ r_c \sin(n\alpha + c2\pi/3 + \phi_c) \\ \frac{d(n+c/3)}{3} \end{bmatrix}, \quad (12)$$

where:  $c \in \{0, 1, 2\}$ , which would be much more complicated if the axes were not coincident. Having not yet investigated in the general case the relationships between  $\alpha$ ,  $r$ ,  $\phi$  and  $d$  in eq. (12) for the three helices, these are denoted with a  $c$  subscript to show they are dependent on the color ( $c \in \{R, B, Y\}$ ). In section 4, we give a more specific version (eq. (14)) of this formula which generates optimal tetrahelices. Since any optimal tetrahelix is described by eq. (12),

$$\text{rad}(\mathbf{V}_{\text{triple}}(n, c)) = \max\{r_R, r_B, r_Y\}$$

Observe that when  $\alpha = 0$ , the helices are degenerate, having curvature of 0, but because of the  $\phi_c$  term, they are not collinear.

In principle, any three helices generated with eq. (12) has at most nine distinct edge length classes. Each edge that connects two rails potentially has a longer length and shorter length we denote with a + or -. So the classes are  $\{RR, BB, YY, RB_+, RB_-, BY_+, BY_-, RY_+, RY_-\}$ . If when projecting all vertices onto the  $z$ -axis (dropping the  $x$  and  $y$  coordinates), the interval defined by the  $z$ -axis value of its endpoints contains no other vertices, we call it a one-hop edge, and if it does contain another vertex we call it a two-hop edge, as illustrated in fig. 9. Then there are 3 rail edges  $\{RR, BB, YY\}$ , 3 one-hop lengths  $\{RB_-, BY_-, RY_-\}$  between each pair of 3 rails, and 3 two-hop lengths  $\{RB_+, BY_+, RY_+\}$  between each pair of 3 rails, where the two-hop length is at least the one-hop length. However, generating the three helices with eq. (12) will cause many of these lengths to be the same. In fact, it is possible that there will be only two distinct such classes, and in fact in the purely regular BC helix there is only one length.

**Theorem 3.** Optimal tetrahelices have the same radius for all three helices.

*Proof.* To prove this theorem, one may exhibit a symmetric tetrahelix (not yet shown to be optimal) which happens to

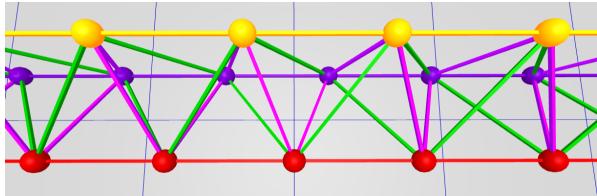


Fig. 10. Equitetrabeam

be a triple helix, that has the property that all rail edges are equal to all one-hop edges and all two-hop edges are equal to each other. Observe that although the formula for the radii of such a triple helix **has not yet been developed**, there are some values for  $r$  and  $\alpha$ , and  $\phi$  in eq. (12) for which all the three helices are symmetrically and evenly spaced. Furthermore, **one** can choose these values such that the three rail edges are of length 1 and so that the one-hop lengths are also all of length 1, and the two-hop lengths are slightly longer.

Now consider a tetrahelix in which the radius of one of the helices is different. By the connections made in a tetrahelix, any increase to a radius increases both a one-hop and two-hop distance, and any decrease likewise decreases two. Since there exists a tetrahelix which has only two distinct classes of edge lengths, the smaller being one-hop = rail, the larger being the two-hop distance, the helix with a larger radius increases a longest edge without increasing a shortest edges. Likewise, a helix with a smaller radius decreases a one-hop edge without decreasing a two-hop edge.

Therefore, a tetrahelix with different radii is not as optimal as some two-class tetrahelix generated by eq. (12), **and so by eq. (10)** is not optimal.

**Although theorem 4 which asserts that a two-class tetrahelix is optimal **has not yet been proven****, it suffices to show that there exists such a better tetrahelix to show that different radii imply a suboptimal tetrahelix.

Because an optimal tetrahelix has equivalent radii and equivalent pitch for all three helices, it has equivalent rail edge lengths. Likewise, there is a single rail angle  $\rho$  that represents the rotation of two vertices connected by a single rail edge, and it is the same for all three rails.

Now that **is proven** that on any optimal tetrahelix the vertices are on helices of the same axes and pitch, **observe** that the vertices of any optimal tetrahelix will lie on a cylinder, or a circle when the axis dimension is projected out. Therefore, it is reasonable to now speak of the singular radius  $r$  of a tetrahelix as the radius of the cylinder. **This allows** the harder proof about where vertices occur along the  $z$ -axis.

**In fact**, the vertices must be distributed in even thirds along the  $z$ -axis as they are in the regular BC helix. **Note that it is already proven that** the rail lengths are equal in any optimal tetrahelix.

Figure 10 shows the equitetrabeam, which is defined in section 6, but also conveniently illustrates the one-hop and two-hop edge definitions. The green edges are the two-hop edges and the purple edges are the one-hop edges. Note that the green edges are slightly longer than the purple edges. In fig. 9, which depicts the BC helix, the two-hop and one-hop

edges are of equal length (but the projection onto the  $z$ -axis, the axial length, of the two-hop edge is longer than the axial one-hop length.)

**Theorem 4.** *An optimal tetrahelix of any rail angle  $0 \leq \rho < \pi$  is a triple helix with all vertices evenly spaced at  $d/3$  intervals on the  $z$ -axis. Any one tetrahedron in a tetrahelix has 1 rail edge, 2 one-hop edges connected to the rail, and 2 two-hop edges connected to the rail. The sixth edge is opposite of the rail edge and is a one-hop edge.*

*Proof.* Consider a tetrahelix in which the vertices are evenly spaced at  $d/3$  intervals on the  $z$ -axis. Every edge is either a rail edge, or it makes one hop, or two hops. All of the one-hop edges are equal length. All of the two-hop edges are equal length.

Every vertex is connected to 4 non-rail edges. There is a one-hop edge in both the positive and negative  $z$  direction. Likewise, there is a two-hop edge in both the positive and negative  $z$  direction. Let  $A$  be the set of edge lengths, which has only 3 members, represented by  $A = \{o, t, r\}$  for the one-hop, two-hop, and rail edge lengths.

Any attempt to perturb any rail in either  $z$  direction lengthens one two-hop edge to  $t'$ , where  $t' > t$  and shortens one one-hop edge  $o' < o$ . Let  $B = \{o', t'\} \cup A$  be the edge lengths of such a perturbed tetrahelix. **The minimax of  $B$  is greater than the minimax of  $A$ :  $R(B) > R(A)$**  since there is a single rail length which cannot be both greater than  $o'$  and  $t'$  and less than  $o'$  and  $t'$ . Therefore, any optimal tetrahelix has all one-hop edges between all rails equal to each other, and all two-hop edges equal to each other, and the  $z$  distances between rails equal. Therefore, vertices are  $d/3$  from each other on the  $z$ -axis.

Note that based on theorem 4, there are only 3 possible lengths in an optimal tetrahelix, and we are justified in classifying edge lengths as *rail*, *one-hop*, or *two-hop*. The one-hop edges are the edges between rails that are closest on the  $z$ -axis, and the two-hop edges are those that skip over a vertex.

Taking all of these results together, each helix in an optimal tetrahelix is congruent to the others, shares an axis, is the same radius, and is evenly spaced axially with the others. An optimal tetrahelix is therefore a *triple helix*, of a radius formulated in eq. (27).

#### 4 Parameterizing Tetrahelices via Rail Angle

We seek a formula to generate optimal tetrahelices that accepts a parameter that allows us to design the tetrahelix conveniently. Please refer back to fig. 7. The pitch of the helix is an obvious choice, but is not defined when the curvature is 0, an important special case. The radius or the axial distance between two vertices on the same rail are possible choices, but perhaps the clearest choice is to build formulae that takes as their input the “rail angle”  $\rho$ . **Define**  $\rho$  to be the angle formed in the X,Y plane with origin  $O$ :  $\angle H(0,0)OH(0,1)$  projecting out the  $z$ -axis and sighting along the positive  $z$ -axis. In other words,  $\rho$  controls how far

a rail edge of a tetrahelix deviates from being parallel with the axis, or the “twistiness” of the tetrahelix. Use the parameter  $\chi = 1$  to indicate a chirality of counter-clockwise, and  $\chi = -1$  for clockwise. Take our coordinate system to be right-handed.

The quantities  $\rho, r, d$  (see fig. 7) are related by the expression:

$$\begin{aligned} 1^2 &= d^2 + (2r \sin \rho/2)^2, \text{ or} \\ d^2 &= 1 - 4r^2(\sin \rho/2)^2. \end{aligned} \quad (13)$$

Checking the important special case of the BC helix, find that this equation indeed holds true, treating  $d$  in this equation as  $3h_{bc}$  as defined by Gray and Coxeter, that is,  $d_{bc} = 3h_{bc}$ , where they are using  $h$  for the axial height from one vertex to the next of a different color, but we use  $d$  to mean the axial distance between vertices of the same color.

The rail angle  $\rho$  also has the meaning that  $2\pi/\rho$  is the number of tetrahedra in a full revolution of the helix.

In choosing  $\rho$ , one greatly constrains  $r$  and  $d$ , but does not completely determine both of them together, so one must treat both as additional parameters.

Rewriting our formulation in terms of  $\rho$ :

$$\begin{aligned} \mathbf{H}_{\text{general}}(\chi, n, c, \rho, d_\rho, r_\rho) &= \\ \left[ \begin{array}{c} r_\rho \cos(\chi \cdot (n\rho + c(\rho + 2\pi)/3)) \\ r_\rho \sin(\chi \cdot (n\rho + c(\rho + 2\pi)/3)) \\ d_\rho(n + c/3) \end{array} \right] \end{aligned} \quad (14)$$

where:  $1 = d_\rho^2 + 4r_\rho^2(\sin \rho/2)^2$ , and  
 $\chi \in \{-1, 1\}$ .

$\mathbf{H}_{\text{general}}$  forces the user to select three values satisfying eq. (13):  $\rho$ ,  $r_\rho$ , and  $d_\rho$ .

Note that when  $\rho = 0$  then  $d_\rho = 1$ , but  $r_\rho$  is not determined by eq. (13).

**Theorem 5.** For rail angles of magnitude at most  $\rho_{bc}$ , tetrahelices generated by  $\mathbf{H}_{\text{general}}$  are optimal in terms of minimum maximum (minimax) ratio of member length when radius is chosen so that the length of the one-hop edge is equal to the rail length.

*Proof.* By theorem 4, one can compute the (at most) three edge-lengths of an optimal tetrahelix by formulae universally quantified by  $n$  and  $c$ :

$$1 = \text{rail} = \|\mathbf{H}_{\text{general}}(n, c, \rho, d_\rho, r) - \mathbf{H}_{\text{general}}(n+1, c, \rho, d_\rho, r)\|, \quad (15)$$

$$\text{one-hop} = \|\mathbf{H}_{\text{general}}(n, c, \rho, d_\rho, r) - \mathbf{H}_{\text{general}}(n, c+1, \rho, d_\rho, r)\| \text{ and}, \quad (16)$$

$$\text{two-hop} = \|\mathbf{H}_{\text{general}}(n, c, \rho, d_\rho, r) - \mathbf{H}_{\text{general}}(n, c+2, \rho, d_\rho, r)\|. \quad (17)$$

This syntax just represents the Euclidean distance between vertices. Thus:

$$\text{one-hop} = \sqrt{\frac{d_\rho^2}{9} + r^2(\sin^2(\rho/3 + \frac{2\pi}{3}) + (1 - \cos(\rho/3 + \frac{2\pi}{3}))^2)} \quad (18)$$

$$\text{where: } d_\rho^2 = 1 - 4r^2(\sin(\rho/2))^2.$$

By similar algebra and trigonometry:

$$\text{two-hop} = \sqrt{\frac{4d_\rho^2}{9} + r^2(\sin^2(2\rho/3 + \frac{4\pi}{3}) + (1 - \cos(2\rho/3 + \frac{4\pi}{3}))^2)}. \quad (19)$$

By definition of minimax edge length optimality eq. (10), we are trying to minimize:

$$R(T(r)) = \frac{\max\{1, \text{one-hop}(r), \text{two-hop}(r)\}}{\min\{1, \text{one-hop}(r), \text{two-hop}(r)\}}.$$

But since  $\text{two-hop}(r) \geq \text{one-hop}(r)$ , this is equivalent to:

$$R(T(r)) = \frac{\max\{1, \text{two-hop}(r)\}}{\min\{1, \text{one-hop}(r)\}}.$$

This quantity will be equal to one of:

$$\frac{\text{two-hop}(r)}{1}, \frac{1}{\text{one-hop}(r)}, \frac{\text{two-hop}(r)}{\text{one-hop}(r)}. \quad (20)$$

We know that both  $\text{one-hop}(r)$  and  $\text{two-hop}(r)$  increase monotonically and continuously with increasing  $r$ . By inspection, it seems likely that we will minimize this set by equating  $\text{one-hop}(r)$  or  $\text{two-hop}(r)$  to 1, but to be absolutely sure and to decide which one, we must examine the partial derivative of the ratio  $\frac{\text{two-hop}(r)}{\text{one-hop}(r)}$  in this range.

Although complicated, we can use Mathematica to investigate the partial derivative of  $\frac{\text{two-hop}(r)}{\text{one-hop}(r)}$  with respect to the radius to be able to understand how to choose the radius to form the minimax optimum.

Let:

$$f_\rho = -\frac{4(\sin^2(\rho/2))}{9}, \quad (21)$$

$$g_\rho = -\frac{16(\sin^2(\rho/2))}{9}, \quad (22)$$

$$j_\rho = \sin^2(\rho/3 + \frac{2\pi}{3}) + (1 - \cos(\rho/3 + \frac{2\pi}{3}))^2, \quad (23)$$

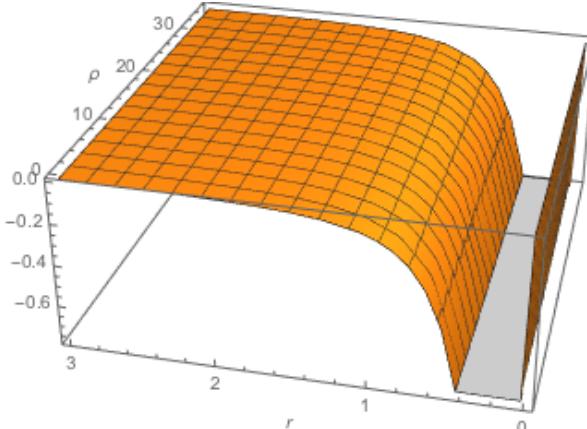


Fig. 11. Partial Derivative against  $\rho$  and  $r$ :  $\frac{\partial \frac{\text{two-hop}(r)}{\text{one-hop}(r)}}{\partial \rho, r}$

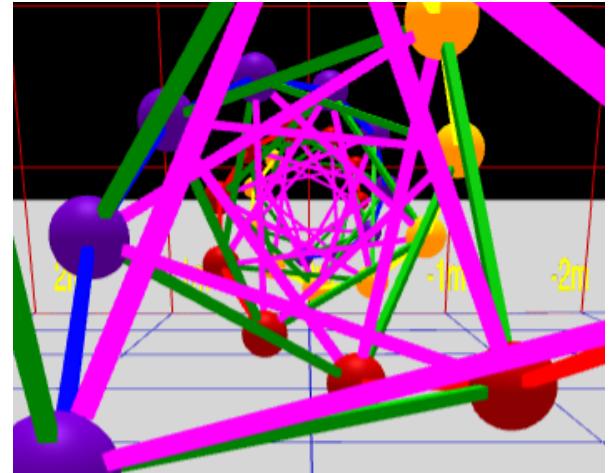


Fig. 12. Axial view of a BC-Helix

and:

$$k_\rho = \sin^2(2\rho/3 + \frac{4\pi}{3}) + (1 - \cos(2\rho/3 + \frac{4\pi}{3}))^2. \quad (24)$$

Then:

$$\frac{\text{two-hop}(r)}{\text{one-hop}(r)} = \frac{\sqrt{\frac{4}{9} + r^2(g_\rho + k_\rho)}}{\sqrt{\frac{1}{9} + r^2(f_\rho + j_\rho)}}. \quad (25)$$

By inspection of the graph of the derivative of this ratio rendered in fig. 11 observe that the partial derivative of this with respect to radius  $r$  is always negative, for any  $\rho \leq \rho_{bc}$ .

When the rail angle approaches  $\pi$ , corresponding to going almost to the other side of the tetrahelix, this is not necessarily true, hence the limitation in our statement of the theorem is meaningful. Since the partial derivative of  $\frac{\text{two-hop}(r)}{\text{one-hop}(r)}$  with respect to the radius  $r$  is negative for all  $\rho$  up until  $\rho_{bc}$ , this ratio goes down as the radius goes up, and one minimizes the maximum edge-length ratio by choosing the largest radius up until one-hop = 1, the rail-edge length. If one attempted to further increase the radius the tetrahelix would not be optimal, because the ratio  $\frac{\text{two-hop}(r)}{1}$  would become the largest ratio in our set of ratios eq. (20).

Therefore, one decreases the minimax length of the whole system as the radius increases up to the point that the shorter, one-hop distance is equal to the rail-length, 1. In order to optimize the whole system so long as  $\rho \leq \rho_{bc}$ , equate one-hop to 1 to find the optimum radius:

$$1 = \sqrt{\frac{\frac{1}{9}}{\sin^2(\rho/3 + \frac{2\pi}{3})} + \frac{r_{opt}^2(-\frac{4(\sin^2(\rho/2))}{9} + (1 - \cos(\rho/3 + \frac{2\pi}{3}))^2)}{(1 - \cos(\rho/3 + \frac{2\pi}{3}))^2}} \quad (26)$$

from which it follows that:

$$r_{opt} = \frac{2}{\sqrt{\frac{9}{2} \cdot (\sqrt{3}\sin(\rho/3) + \cos(\rho/3)) + \cos(\rho) + 8}}. \quad (27)$$

This leads to a formula for  $d_{opt}$  computed from  $\rho, r_{opt}$  via the rail angle equation eq. (13):

$$d_{opt}^2 = 1 - 4(r_{opt})^2(\sin \rho/2)^2, \quad (28)$$

which is expanded to:

$$d_{opt}^2 = 1 - \frac{16(\sin \rho/2)^2}{\frac{9}{2}(\sqrt{3}\sin(\rho/3) + \cos(\rho/3)) + \cos(\rho) + 8} \quad (29)$$

and then rewrite:

$$d_{opt} = \sqrt{1 - \frac{16\sin^2(\rho/2)}{\cos(\rho) + \frac{9}{2}(\sqrt{3}\sin(\rho/3) + \cos(\rho/3)) + 8}}. \quad (30)$$

Thus, by computing  $r_{opt}$  and  $d_{opt}$  as a function of  $\rho$  from this equation, one can construct a minimax optimal tetrahelix where  $0 \leq \rho \leq \rho_{bc}$ .

## 5 The Inradius

Since the axes are parallel, one may define the *inradius*, represented by  $r_{in}$ , of a tetrahelix to be the radius of the largest cylinder parallel to this axis that is surrounded by each tetrahelix and penetrated by no edge.

If one looks down the axis of an optimal tetrahelix as shown in fig. 12, it happens that only the one-hop edges (rendered in purple in our software) comes closest to the axis. In other words, they define the radius of the incircle of the projection, or the radius of a cylinder that would just fit inside

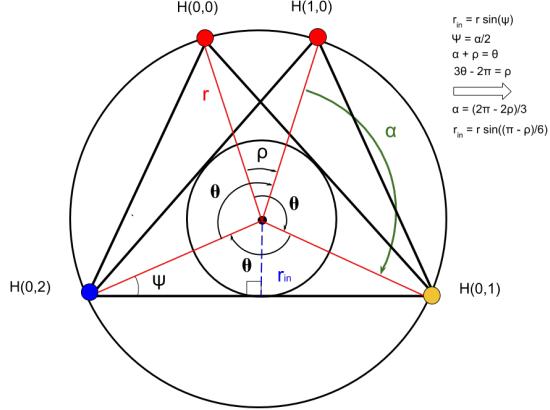


Fig. 13. General One-hop Projection Diagram

the tetrahelix. A formula for the inradius of the tetrahelix is useful if you are designing it as a structure that bears something internally, such as a firehose, a pipe, or a ladder for a human. The inradius  $r_{in}(\rho)$  of an optimal tetrahelix is a remarkably simple function of the radius  $r$  and the rail angle  $\rho$ :

$$r_{in}(\rho) = r \sin \frac{\pi - \rho}{6}, \quad (31)$$

which can be seen from the trigonometry of a diagram of the projected one-hop edges connecting four sequentially numbered vertices, shown in fig. 13.

From this equation, with the help of symbolic computation, one may observe that the inradius of the BC helix of unit rail length is  $r_{in}(\rho_{bc}) = \frac{3}{10\sqrt{2}} \approx 0.21$ .

## 6 The Equitetrabeam

Just as  $H_{general}$  constructs the BC helix (with careful and non-obvious choices of parameters) which is an important special case due to its regularity, it constructs an additional special (degenerate) case when the rail angle  $\rho = 0$  and  $d = 1$  (the edge-length), where the cross sectional area is an equilateral triangle of unchanging orientation, as shown in fig. 10 and at the rear of fig. 3. We call this the *equitetrabeam*, a portmanteau of “equilateral tetrahedral beam”. It is not possible to generate an equitetrabeam from eq. (3) without the split into three rails introduced by eq. (4) and completed in eq. (14).

**Corollary 1.** *The equitetrabeam with minimum maximum edge ratio is produced*

by  $H_{general}$  when  $r = \sqrt{\frac{8}{27}}$  and the longest member is  $\frac{2}{\sqrt{3}}$ , which is less than 16% longer than the shortest member.

*Proof.* Choosing  $d = 1$  and  $\rho = 0$  one can use eq. (27) to find the radius of optimal minimax difference. Substituting

into eq. (14) and setting one-hop<sup>1</sup> to 1 gives:  $1 = \sqrt{\frac{1}{9} + 3r^2}$ , or  $r = \sqrt{\frac{8}{27}}$ . This radius produces a two-hop edge length of  $\frac{2}{\sqrt{3}} \approx 1.1547$ .

The inradius of the equitetrabeam of unit rail length from both eq. (31) and the fact that the inradius of an equilateral triangle is half the circumradius is  $\sqrt{\frac{8}{27}}/2$ , or  $\frac{\sqrt{6}}{9}$ .

In fig. 3, the furthest tetrahelix is the optimal equitetrabeam. Figure 10 is a closeup of an equitetrabeam.

To the extent that one values tetrabeams (that is, tetrahelices with a rail angle of 0, and therefore zero curvature) as mathematical or engineering objects, this paper has motivated the development of  $H_{general}$  as a transformation of  $V(n)$  defined by eq. (3) from Gray and Coxeter.

The equitetrabeam may possibly be a novel construction. The fact that 6 members meet in a single point would have been a manufacturing disadvantage that may have dissuaded structural engineers from using this geometry. However, the advent of additive manufacturing, such as 3D printing, and the invention of two distinct concentric multi-member joints [4,5] has improved that situation.

Note that the equitetrabeam has chirality, which becomes important in our attempt to build a continuum of tetrahelices.

## 7 An Untwisted Continuum

Observe that eqs. (27) and (30) compute  $r_{opt}$  and  $d_{opt}$  which create an optimal tetrahelix for any rail angle  $\rho$  between 0, which gives the equitetrabeam and  $\rho_{bc} \approx 35.43^\circ$ , which gives the BC helix.

Because the equitetrabeam which has a rail angle of 0 still has chirality, that is, one still must decide to connect the one-hop edge to the clockwise or the counter-clockwise vertex, it is not possible to build a smooth continuum where  $\rho$  transitions from positive to negative which remains optimal. One can use a negative  $\rho$  in  $H_{general}$  but it does not produce minimax optimal tetrahelices. In other words, untwisting a counter-clockwise tetrahelix to rail angle 0 and then going even further does produce a clockwise tetrahelix, but one in which the one-hop and two-hop lengths in the wrong places, that is, two-hop becomes shorter than one-hop. Likewise,  $\rho > \rho_{bc}$  generates a tetrahelix, but its optimality has not been proved or investigated in that range.

The pitch of a helix for a known  $z$ -axis travel  $d$  is trivial (see eq. (7)). If one is varying  $\rho$  to obtain a desired pitch from eq. (30) and eq. (7) it is not so simple. However, the pitch increases monotonically and smoothly with decreasing  $\rho$ , so eq. (7) can be easily solved numerically with a Newton-Raphson solver, as is done on our website. For a pitch at least  $p \geq \frac{3\sqrt{2}\pi}{\sqrt{5}\rho_{bc}} \approx 9.64$ , using eq. (30) produces minimax optimal tetrahelices.

<sup>1</sup>Before developing the optimal solution eq. (27) we found another interesting but non-optimal tetrabeam of zero curvature by setting the mean of one-hop and two-hop to 1 ((one-hop + two-hop)/2 = 1), which gives  $r = \sqrt{35}/4$  and three length classes of  $\frac{11}{12}, \frac{12}{12}, \frac{13}{12}$ .

In this way, a rail angle can be chosen for any desired (sufficiently large) pitch, yielding the optimum radius, the one-hop length, and the two-hop length that an engineer needs to construct a physical structure.

The curvature of a rail helix is formally given by:

$$\frac{|r_\rho|}{r_\rho^2 + (d_\rho/\rho)^2}. \quad (32)$$

which goes to 0 as  $\rho$  approaches 0 (the equitetrabeam.) As  $\rho$  increase up to  $\rho_{bc}$  the curvature increases smoothly until the BC helix is reached.

Perhaps surprisingly, the optimal untwisting is accomplished only by changing the length of the two-hop member, leaving the one-hop member and rail length equivalent within this continuum.<sup>2</sup> However, it should be noted that an engineer or architect may also use **H**<sub>general</sub> directly and interactively via <https://pubinv.github.io/tetrahelix/>, and that minimax length optimality is a mathematical starting point rather than the final word on the beauty and utility of physical structures. For example, a structural engineer might increase a radius past optimality in order to resist buckling.

If an equitetrabeam were actually used as a beam, an engineer might start with the optimal tetrabeam and dilate it in one dimension to stiffen the beam by deepening it. Similarly, simple length changes curve the equitetrabeam into an arch. The “colored” approach of eq. (14) exposes these possibilities more than the approach of eq. (3).

## 8 Conclusion

It is proven there exists a continuum of minimax edge-length optimal tetrahelices having as one end the completely regular Boerdijk-Coxeter helix and at the other end a completely untwisted tetrahelix with equilateral cross section and planar faces, the equitetrabeam. By changing the length of only one out of three members by less than 16%, all configurations in the continuum may be reached. All such optimal tetrahelices may provably be generated by a simple equation giving coordinates or by selecting appropriate edge lengths generated from the same equation. A machine, such as the Tetrobot or a variable-geometry truss depicted in fig. 5, that can change the length of some of its members by 16% can thus twist and untwist itself. A completely regular Tetrobot can untwist itself to create a planar face on the ground for locomotion via standard gaits. With a numeric solution, a designer may choose a rotation angle to obtain an optimal tetrahelix design of any pitch, including rational ones.

### 8.1 Contact and Getting Involved

The Tetrobot Project:

<http://pubinv.github.io/tetrobot/> is part of

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<sup>2</sup>Before deriving eq. (27), a continuum was created by using a linear interpolation between the optimal radius for the equitetrabeam and the BC helix. This minimax optimum of this simpler approach was at most 1% worse than the optimum computed by eq. (27).

Public Invention, a free-libre, open-source research, hardware, and software project that welcomes volunteers. To assist, contact: [read.robert@gmail.com](mailto:read.robert@gmail.com).

## 8.2 Acknowledgment

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