Geometric Restrictions on Producible Polygonal Protein Chains

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Abstract. Fixed-angle polygonal chains in 3D serve as an interesting model of protein backbones. Here we consider such chains produced inside a "machine" modeled crudely as a cone, and examine the constraints this model places on the producible chains. We call this notion *α-producible*, and prove as our main result that a chain is α-producible if and only if it is flattenable, that is, it can be reconfigured without self-intersection to lie flat in a plane. This result establishes that two seemingly disparate classes of chains are in fact identical. Along the way, we discover that all α-producible configurations of a chain can be moved to a canonical configuration resembling a helix. One consequence is an algorithm that reconfigures between any two flat states of a nonacute chain in $O(n)$ "moves," improving the $O(n^2)$-move algorithm in [ADD$^+$02]. Finally, we prove that the α-producible chains are rare in the following technical sense. A random chain of n links is defined by drawing the lengths and angles from any "regular" (e.g., uniform) distribution on any subset of the possible values. A random configuration of a chain embeds into $\mathbb{R}^3$ by in addition drawing the dihedral angles from any regular distribution. If a class of chains has a locked configuration (and we know of no nontrivial class that avoids locked configurations), then the probability that a random configuration of a random chain is α-producible approaches zero geometrically as $n \to \infty$.

1 Introduction

The backbone of a protein molecule may be modeled as a 3D polygonal chain, with fixed link (edge) lengths. The joints are not universal; rather the bonds between residues form nearly fixed angles in space. The motions at the joints are then called *dihedral* motions. The study of such *fixed-angle* chains was initiated in [ST00] and continued in [ADM$^+$02] and [BDD$^+$02]. These papers identified *flat states* of a chain—embeddings into a plane without self-intersection—as

⋆ Chargé de recherches du FNRS.

⋆⋆ Supported by NSF Distinguished Teaching Scholars award DUE-0123154.

geometrically interesting. A chain that can reconfigure in $\mathbb{R}^3$ via dihedral motions between any two of its flat states is called *flat-state connected*. A chain that has a flat state but is in a configuration that cannot reach that state (via dihedral motions, without self-intersection) is called *unflattenable* or simply *locked*.[1]

We look here at a particularly simple but natural constraint on the "production" of a fixed-angle chain. Our inspiration derives from the ribosome, which is the "machine" that creates protein chains in biological cells. However, we quickly deviate from reality and replace the ribosome by a simple geometric constraint: the chains are produced inside a cone of half-angle $\alpha \leq \pi/2$, emerging through its apex.

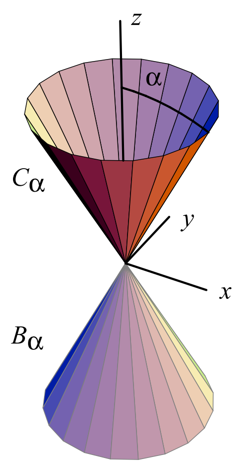

Fig. 1. The chain is produced in C_α, and emerges at the origin into the complimentary cone B_α below the xy-plane.

We show in Section 3 that this simple constraint guarantees that all producible chains are flattenable and furthermore mutually reachable. There are several interesting aspects to this result. First, cones with $\alpha > \pi/2$ (concave cones) permit the production of locked chains, as shown in Section 4, so the $\leq \pi/2$ constraint is needed. Second, we are naturally led in our proof to a canonical form, called α-CCC, which bears a resemblance to the helical form preferred by many proteins. Third, we show in Section 5 that long "random" chains are locked with probability approaching 1, implying that producible protein chains are rather special.

2 Definitions

2.1 Chains and Motions

The fixed-angle polygonal chain P has $n+1$ vertices $V = \langle v_0, \ldots, v_n \rangle$ and is specified by the fixed turn angle θ_i at each vertex v_i, $i = 1, \ldots, n-1$, and by the edge length d_i between v_i and v_{i+1}, $i = 0, \ldots, n-1$. When all angles $\theta_i \leq \alpha$ for some $0 < \alpha \leq \pi/2$, P is called a *$(\leq \alpha)$-chain*. We write $P[i,j]$, $i \leq j$, for the polygonal subchain composed of vertices $v_i, \ldots, v_j$.

A *configuration* $Q = \langle q_0, \ldots, q_n \rangle$ of the chain P (see Fig. 2) is an embedding of P into $\mathbb{R}^3$, i.e., a mapping of each vertex v_i to a point $q_i \in \mathbb{R}^3$, satisfying the constraints that the angle between vectors $q_{i-1}q_i$ and q_iq_{i+1} is θ_i, and the distance between q_i and q_{i+1} is d_i. The points q_i and q_{i+1} are connected by a straight line segment e_i. Thus, a configuration can be specified by the position of e_0 and dihedral angles δ_i, $i = 1, \ldots, n-2$, where δ_i is the angle between planes $e_{i-1}e_i$ and e_ie_{i+1}. The configuration is *simple* if no two nonadjacent segments intersect.

[1] In fact, this definition is slightly more specific than the usual notion of "locked," which says that there are two arbitrary configurations of the linkage that are mutually unreachable.

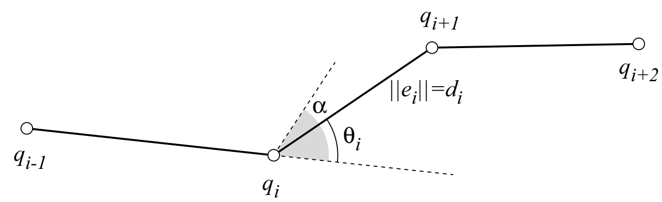

Fig. 2. Notation for a configuration Q.

A *motion* $M = \langle m_0, \ldots, m_n \rangle$ of a chain P is a list of $n+1$ continuous functions $m_i : [0, \infty] \to \mathbb{R}^3$, $i = 0, \ldots, n$, such that $M(t) = \langle m_0(t), \ldots, m_n(t) \rangle$ is a configuration of P for all $t \in [0, \infty]$. The motion is said to be *simple* if all such configurations $M(t)$ are simple. We normally assume that the motion is *finite* in the sense that, after some time T, M becomes independent of t.

2.2 Chain Production

As mentioned above, our model is that the chain is produced inside an infinite open cone C_α with apex at the origin, axis on the z axis, and half-angle (to the positive z-axis) $\alpha \leq \pi/2$; see Fig. 1. Let $\overline{C}_\alpha$ be the corresponding closed cone. We similarly define the cone B_α, the mirror image of C_α with respect to the xy-plane.

The vertices and edges are created inside $\overline{C}_\alpha$ and exit the machine at the apex of $\overline{C}_\alpha$. The portion of the chain already produced is allowed to move freely as long as it stays simple and never meets C_α. At time $t_0 = 0$, the machine creates v_0 at the apex of C_α, v_1 inside $\overline{C}_\alpha$, and the segment e_0 connecting them. In general, at time t_i, vertex v_i reaches the apex of $\overline{C}_\alpha$, and v_{i+1} and e_i are created inside $\overline{C}_\alpha$. The vertex v_i stays in $\overline{C}_\alpha$ between times t_{i-1} and t_i and $0 = t_0 < t_1 < \cdots < t_n$.

Formally, an *α-production* F is a set of $n+1$ continuous functions f_i : $[t_{i-1}, \infty] \to \mathbb{R}^3$, $i = 0, \ldots, n$, such that, for all $t \in [t_{j-1}, t_j]$, $f_j(t) \in \overline{C}_\alpha$, $F(t) = \langle f_0(t), \ldots, f_j(t) \rangle$ is a simple configuration of $P[0, j]$, and no segment e_i intersects C_α, $i < j$. A configuration Q is said to be *α-producible* if there exists an α-production F with $F(\infty) = Q$.

One consequence of this model is the following:

Lemma 1. *An $(\leq \alpha)$-chain can be produced only in a cone $C_{\alpha/2}$ or larger.*

Proof. Suppose $\theta_i = \alpha$. At time t_i, when v_{i+1} is created inside the cone, v_i is at the apex, and v_{i-1} is outside. Because we stipulate continuous motion, v_{i-1} must be inside the cone $\overline{B}_{\alpha/2}$ below the xy-plane, for it must have been there throughout $t \in [t_{i-1}, t_i)$. If e_{i-1} is on that cone surface, then v_{i+1} can just barely be inside $\overline{C}_{\alpha/2}$, on its surface, with turn angle α at v_i. Note that, for $t > t_i$, v_{i-1} need no longer remain in $\overline{B}_{\alpha/2}$. □

We will prove that there exists a simple motion between any two α-producible configurations of the same chain, and that all such configurations are flattenable. Next we define the notion of a "simple" motion.

2.3 Complexity of a Motion

There are of course many ways to define the complexity of a motion M. As a first approximation, we could assume that each dihedral angle $\delta_i^M(t)$ of the segment e_i is a piecewise-linear function of time t, and the complexity $T(M)$ of the motion M is the total number of linear pieces over all functions $\delta_i^M(t)$. That is, $T(M) = \sum_{i=1}^{n-2} T(\delta_i^M)$, where $T(\delta_i^M)$ is the number of linear pieces in the function δ_i^M. Unfortunately, this definition is not acceptable, as it restricts the range of possible motions M. The definition can be generalized to allow arbitrary functions $\delta_i^M(t)$, given some corresponding measure of complexity $T(\delta_i^M)$, with the added restriction that for every time range $t \in [r, s]$ during which $\delta_i^M(t)$ is a linear function, that time range contributes at most 1 to the complexity $T(\delta_i^M)$. For example, if $\delta_i^M(t)$ is a piecewise-polynomial function, $T(\delta_i^M)$ could be defined as the sum of the degrees of the polynomial pieces; or more generally $T(\delta_i^M(t))$ might measure the number of inflection points or monotonic pieces of $\delta_i^M(t)$.

The complexity of a production F can be defined in an analogous way, where $\delta_i^F(t)$ is defined only for the time range $t \geq t_{i+1}$. The resulting value will only account for the dihedral motions outside the cone C_α. We still need to add the complexity of the movement of point $f_{i+1}(t)$ before it exits the cone for all i, i.e., at time $t \in [t_i, t_{i+1})$. If we assume that the chain exits the cone at a constant rate, we only need to consider the vector $u^F(t) = (0, f_{i+1}(t))$ for $t \in [t_i, t_{i+1})$, described in polar coordinates by the angle $\rho^F(t)$ of $u^F(t)$ with the z-axis, and the angle $\gamma^F(t)$ of the projection of $u^F(t)$ onto the xy-plane with the x-axis. The complexity will be expressed by $T(\gamma^F)$ and $T(\rho^F)$, with the restriction that $T(\rho^F)$ be at least the number of connected components in $\{t : \rho^F(t) = 0\}$. For example, the number of pieces in a piecewise-linear function, or the sum of degrees in a piecewise-polynomial function, would qualify. No restrictions are imposed on $T(\gamma^F)$. The total complexity of the production is then $T(F) = \sum_{i=1}^{n-2} T(\delta_i^F) + T(\rho^F) + T(\gamma^F)$.

3 Producible $\equiv$ Flattenable

Key to our main theorem is showing that every α-producible configuration can be moved to a canonical configuration, and therefore to every other α-producible configuration.

3.1 Canonical Configuration

We begin by defining the canonical configuration of α-producible chains, called the *α-cone canonical configuration* or *α-CCC*. To better understand the constraints of a configuration Q, consider normalizing all edge vectors $q_i q_{i+1}$ to unit vectors $u_i = (q_{i+1} - q_i)/\|q_{i+1} - q_i\|$ which lie on the unit sphere. The α-CCC is constructed to have the property that all such vectors lie along a circle of radius $\alpha/2$ on that sphere. In other words, the vectors u_i lie on the boundary of a cone with half-angle $\alpha/2$.

To ease the description, we use the cone $\overline{C}_{\alpha/2}$ (not C_α) to define α-CCC, but note that the cone and the chain could be rotated and translated. By convention, we place u_0 on the boundary of $\overline{C}_{\alpha/2}$ in the positive quadrant of the yz-plane. Because Q is a configuration of P, the angle between u_{i-1} and u_i is θ_i and so, on the sphere, u_i lies on the circle of radius θ_i centered at u_{i-1}. Because $\theta_i \leq \alpha$, this circle intersects the boundary of $\overline{C}_{\alpha/2}$. We set u_i to be the first intersection counterclockwise from u_{i-1} on the boundary of $\overline{C}_{\alpha/2}$ (where counterclockwise is viewed from the origin). See Fig. 3 for an example.

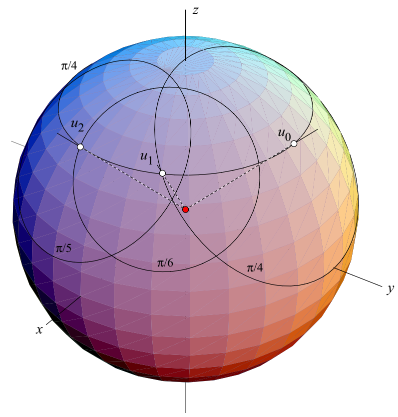

Fig. 3. u_0 lies on the cone $C_{\pi/4}$. $(\theta_1, \theta_2, \theta_3) = (\pi/4, \pi/6, \pi/5)$, respectively.

The position of the u_i's on the unit sphere as described above, along with the position of q_0, uniquely determine the position of the α-CCC of the chain. Because the u_i vectors all have positive z coordinates, we know that the resulting configuration is simple. We can also show that the α-CCC is completely contained in $\overline{C}_{\alpha/2}$:

Lemma 2. *If all unit edge vectors u_i are contained in a cone $\overline{C}_\beta$ for some half-angle $\beta > 0$, then the configuration Q is inside $q_0 + \overline{C}_\beta$, the cone translated so its apex is at q_0. Furthermore, if $u_0 \neq u_1$, then only the first bar of the chain can touch the boundary of $q_0 + \overline{C}_\beta$.*

Proof. The proof is by induction on n. The claim holds for the 1-point chain $Q[n, n]$. Assume $Q[1, n]$ is contained in a cone with apex q_1. Now q_1 is on the boundary of the cone with apex q_0, so the cone with apex at q_1 is contained in the one with apex at q_0. Furthermore, the boundary of these cones intersect only at the line of support $q_0 q_1$. □

In the α-CCC, u_i is always different from u_{i+1}.

3.2 Canonicalization

Next we show how to find a motion from any α-producible configuration of an α-producible chain to the corresponding α-CCC.

Theorem 1. *If a configuration Q of a $(\leq \alpha)$-chain P is α-producible by a production F, then there is a motion M from Q to the α-CCC, with $T(M) \leq T(F) + 3n$.*

Proof. Because Q is α-producible, there exists an α-production F with $F(\infty) = Q$. By scaling time appropriately, we can arrange that $t_i = i$, and the configuration freezes at time $n+1$, i.e., $F(t) = F(n+1)$ for $t > n+1$.

We construct a motion M from Q to the α-CCC, constructed inside $\overline{C}_\alpha$. A key idea in our construction is to play the production movements backwards. More precisely, for all $i = 0, \ldots, n$, we define $m_i(t) = f_i(n+1-t)$ for the (reverse) time interval $t \in [0, n+2-i]$. (Beyond reverse time $n+2-i$, the original production time is less than $n+1-(n+2-i) = i-1$ and thus f_i is no longer defined.) To complete the construction, we just have to define $m_i(t)$ for $t > n+2-i$, that is, the motion of the part of the chain that has already re-entered the cone $\overline{C}_\alpha$.

During the time interval $(n-i, n+1-i)$, the edge e_i is entering the cone $\overline{C}_\alpha$ through the origin, $P[0,i]$ is outside C_α, and $P[i+1,n]$ is inside C_α. We maintain the invariant that $P[i,n]$ is in α-CCC, contained in a cone $\overline{C}_{\alpha/2}$ translated and rotated to some position $\overline{C}'_{\alpha/2}$. So the dihedral angle of e_j does not change for $j > i$, i.e., $P[i+1,n]$ is held rigid. Because $P[0,i]$ moves freely outside of C_α according to the reversed movements of the α-production, we can only control the dihedral angle of e_i in order to maintain that $\overline{C}'_{\alpha/2}$ (and so $P[i+1,n]$) stays inside $\overline{C}_\alpha$.

Again, consider the vectors u_j. The invariant means that all u_j, $j = i, \ldots, n-1$, touch the boundary of some circle σ of radius $\alpha/2$ on the unit sphere centered on the apex of the cone, and σ must be inside $\overline{C}_\alpha$. The last condition will be true whenever σ contains the unit vector u_{+z} along the z-axis, because we selected σ to have radius $\alpha/2$, so it has diameter α, which is the angle between u_{+z} and the side of C_α. Thus, for any position u_i, we place σ so that its diameter from u_i contains u_{+z}. As long as $u_i \neq u_{+z}$, this position is unique and the resulting motion is continuous because the production is continuous. When $u_i = u_{+z}$, a discontinuity might be introduced, but these discontinuities can easily be removed by stretching the moment of time at which a discontinuity occurs and filling in a continuous motion between the two desired states.

At time $t = n+1-i$, vertex i enters $\overline{C}_\alpha$ and the invariant needs to be restored for the next phase. At that time, the vector u_{i-1} lies in $\overline{C}_\alpha$, and u_i is on a circle τ of radius θ_i centered at u_{i-1}. Let σ' be the desired new position for σ, that is, the circle whose diameter is α, passes through u_{i-1}, and contains u_{+z}. We know that σ' and τ intersect and all intersections are inside $\overline{C}_\alpha$ because σ' is in $\overline{C}_\alpha$. We first move u_i to the first intersection between σ' and τ counterclockwise from u_{i-1} on σ' by changing the dihedral angle of e_{i-1}, and simultaneously moving σ accordingly as described above by changing the dihedral angle of e_i. We then rotate σ about u_i to the position σ' by changing the dihedral angle of e_i. This motion can be done in such a way that σ always contains u_{+z}, because the set of dihedral angles of e_i for which σ contains u_{+z} is connected.

The complexity of all dihedral motions outside of C_α is $\sum_{i=1}^{n-2} T(\delta_i^F)$. The dihedral motions of e_i during times $t \in (n-i, n+1-i)$ mirror exactly $\gamma^F(n+1-t)$, except at discontinuities, which correspond to times for which $u_i = u_{+z}$, which is exactly when $\rho^F(n+1-t) = 0$, so the total complexity of these dihedral motions is bounded by $C(\rho^F)+C(\gamma^F)$. Finally, whenever a vertex attains the apex of the cone, we perform three dihedral rotations (linear functions of time) to restore the invariant. Summing it all, we obtain $C(M) \le \sum_{i=1}^{n-2} T(\delta_i^F) + C(\rho^F) + C(\gamma^F) + 3n = C(F) + 3n$. □

Corollary 1. *For any two simple α-producible configurations Q_1 and Q_2 of a common chain, with respective productions F_1 and F_2, there is a simple motion M from Q_1 to Q_2—that is, $M(0) = Q_1$ and $M(\infty) = Q_2$—for which $T(M) \le T(F_1) + T(F_2) + 6n$.*

Proof. Because Q_1 and Q_2 are α-producible, the previous theorem gives us two motions M_1 and M_2 with $M_1(0) = Q_1$, $M_1(\infty) = \alpha$-CCC, $M_2(0) = Q_2$, and $M_2(\infty) = \alpha$-CCC. By rescaling time, we can arrange that $M_1(t) = M_2(t) = \alpha$-CCC for t beyond some time T. Then define $M(t) = M_1(t)$ for $0 \le t \le T$, $M(t) = M_2(2T - t)$ for $T < t \le 2T$, and $M(t) = Q_2$ for $t > 2T$. □

3.3 Connection to Flat States

Finally, we relate flat configurations to productions and prove our main result that flattenability is equivalent to producibility.

Lemma 3. *All flat configurations of a $(\le \alpha)$-chain have an α-production F for $\alpha \le \pi/2$. Furthermore, $T(F) \le n$.*

Proof. Assume the configuration is in the xy-plane. Any such flat configuration can be created using the following process. First, draw e_0 in the xy-plane. Then, for all consecutive edges e_i, create e_i in the vertical plane through e_{i-1} at angle θ_{i-1} with the xy-plane, then rotate it to the desired position in the xy-plane by moving the dihedral angle of e_{i-1}. During the creation and motion of e_i, it is possible to enclose it in some continuously moving cone C of half-angle α whose interior never intersects the xy-plane: at the creation of e_i, C is tangent to the xy plane on the support line of e_{i-1} and with its apex at p_i. During the rotation of e_i, e_i will eventually touch the boundary of C. We then move C along with e_i so that both e_i and the xy-plane are tangent to C. When e_i reaches the xy plane, we translate C along e_i until its apex is p_{i+1}. Viewing the construction relative to C and placing C on C_α gives the desired α-production. □

Corollary 2. *$(\le \pi/2)$-chains are flat-state connected. The motion between any two flat configurations uses at most $8n$ dihedral motions.*

Proof. Consider two flat configurations Q and Q' of a $(\le \pi/2)$-chain. By Lemma 3, Q and Q' are both $(\pi/2)$-producible, and so by Corollary 1, there exists a motion M such that $M(0) = Q$ and $M(+\infty) = Q'$. □

Corollary 3. *All α-producible configurations are flattenable, provided $\alpha \le \pi/2$. For a production F, the flattening motion M has complexity $T(M) \le T(F)+7n$.*

Proof. Consider an α-producible configuration Q of an $(\le \alpha)$-chain P. Because $\alpha \le \pi/2$, the chain P also has a flat configuration Q' [ADD+02]. By Lemma 3, Q' is producible, and so by Corollary 1, there exists a motion M such that $M(0) = Q$ and $M(+\infty) = Q'$. □

4 A More Powerful Machine

We now show that, under a different model, our result does not hold. Suppose that v_{i+1} is not created at t_i, but rather imagine the time instant t_i stretched into a positive-length interval $[t_i, t'_i]$, allowing time for $v_i v_{i-1}$ to rotate exterior to the cone prior to the creation of v_{i+1} (at time t'_i). This flexibility would remove the connection in Lemma 1 between the half-angle of the cone and the turn angles produced, permitting chains of large turn angle to be produced. Indeed, the sequence of motions depicted in Fig. 4 exploits this large-angle freedom to emit a 4-link fixed-angle chain that is locked.

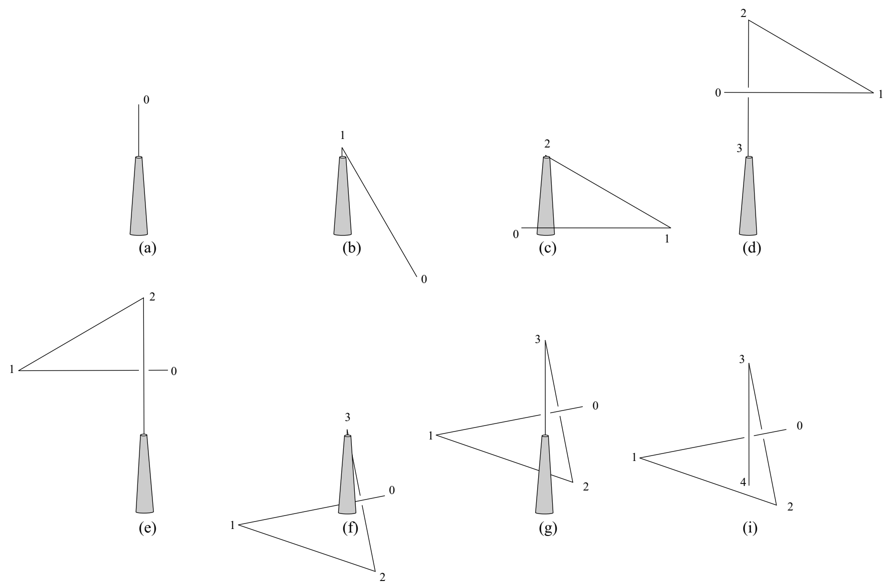

Fig. 4. Production of a locked chain under a model that permits large turning angles to be created. For clarity, the cone is reflected to aim upward. (a) $e_0 = (q_0, q_1)$ emerges; (b) turn at q_1; (c) turn at q_2 and dihedral motion at q_1 places e_1 in front of cone; (d) e_2 nearly fully produced; (e) chain spun about e_2 (or viewpoint changed); (f) rotation at q_3 away from viewer places chain behind cone; (g) e_3 emerges; (i) final locked chain shown loose; the turn angle θ_3 at q_3 can be made arbitrarily close to π.

It is possible to view this model as the same as the previous, but with an $\alpha > \pi/2$, so that the chain inside C_α can form angles at the apex as large as 2α, which could approach 2π.

5 Random Chains

This section proves that the producible/flattenable configurations are a vanishingly small subset of all possible configurations of a chain, for almost any chain. Essentially, the results below say that, if there is one configuration of one chain in a class that is unflattenable, then a randomly chosen configuration of a randomly chosen chain from that class is unflattenable with probability approaching 1 geometrically as the number of links in the chain grows. Furthermore, this result holds for any "reasonable" probability distribution on chains and their configurations.

To define probability distributions, it is useful to embed chains and their configurations into Euclidean space. A chain $P = \langle \theta_1, \ldots, \theta_{n-1}; d_0, \ldots, d_{n-1} \rangle \in [0, \pi/2]^{n-1} \times [0, \infty)^n$ is specified by its turn angles θ_i and edge lengths d_i. A configuration $Q = \langle \delta_1, \ldots, \delta_{n-2} \rangle \in [0, 2\pi)^{n-2}$ of P is specified by its dihedral angles. We also need to be precise about our use of the term "unflattenable" for chains vs. configurations. A simple configuration Q is *unflattenable* or simply *locked* if it cannot reach a flat configuration; a chain P is *lockable* if it has a locked configuration.

We consider the following general model of random chains of size n. Call a probability distribution *regular* if it has positive probability on any positive-measure subset of some open set called the *domain*, and has zero probability density outside that domain.[2] For Euclidean d-space $\mathbb{R}^d$, a probability distribution is regular if it has positive probability on any positive-radius ball inside the domain. Uniform distributions are always regular.

For chains of k links, we emphasize the regular probability distribution $\mathcal{P}_k^{\Theta,\mathcal{D}}$ obtained by drawing each turn angle θ_i independently from a regular distribution Θ, and drawing each edge length d_i independently from a regular distribution $\mathcal{D}$. Similarly, for not-necessarily-simple configurations of a fixed chain P, we emphasize the regular probability distribution obtained by drawing each dihedral angle δ_i independently from a regular distribution Δ. We can modify this probability distribution to have a domain of all simple configurations of P instead of all configurations of P, by zeroing out the probability density of nonsimple configurations, and rescaling so that the total probability is 1. The resulting distribution is denoted $\mathcal{Q}^{P,\Delta}$, and it is regular because the subspace of simple configurations of a chain P is open.

First we show that individual locked examples immediately lead to positive probabilities of being locked. The next lemma establishes this property for configurations of chains, and the following lemma establishes it for chains.

Lemma 4. *For any regular probability distribution $\mathcal{Q}$ on simple configurations of a lockable chain P, if there is a locked simple configuration in the domain of $\mathcal{Q}$, then the probability of a random simple configuration Q of P being locked is at least a constant $c > 0$.*

Lemma 5. *For any regular probability distribution $\mathcal{P}$ on chains, if there is a lockable chain in the domain of $\mathcal{P}$, then the probability of a random chain P being lockable is at least a constant $\rho > 0$.*

Next we show that these positive-probability examples of being locked lead to increasing high probabilities of being locked as we consider larger chains.

[2] A closely related but more specific notion of regular probability distributions in 1D was introduced by Willard [Wil85] in his extensions to interpolation search.

Theorem 2. *Let P_n be a random chain drawn from the regular distribution $\mathcal{P}_n^{\Theta,\mathcal{D}}$. If there is a lockable chain in the domain of $\mathcal{P}_n^{\Theta,\mathcal{D}}$ for at least one value of n, then $\lim_{n\to\infty} Pr[P_n \text{ is lockable}] = 1$. Furthermore, if Q_n is a random simple configuration drawn from the regular distribution $\mathcal{Q}^{P_n}$, then $\lim_{n\to\infty} Pr[Q_n \text{ is flattenable}] = \lim_{n\to\infty} Pr[Q_n \text{ is producible}] = 0$. Both limits converge geometrically.*

Proof. Suppose there is a lockable chain of k links. By Lemma 5, $\Pr[P_k \text{ is lockable}] > \rho > 0$. Break P_n into $\lfloor n/k \rfloor$ subchains of length k. Each of these subchains is chosen independently from $\mathcal{P}_k^{\Theta,\mathcal{D}}$ and is not lockable with probability $< 1-\rho$. Now P_n is lockable (in particular) if any of the subchains are lockable, so the probability that P_n is not lockable is $< (1-\rho)^{\lfloor n/k \rfloor}$ which approaches 0 geometrically as n grows. Likewise, by Lemma 4, the probability that Q_k is locked is $> c\rho$ for some constant $0 < c < 1$, and so the probability that Q_n is flattenable is $< (1-c\rho)^{\lfloor n/k \rfloor}$ which approaches 0 as n grows. □

Thus, producible configurations of chains become rare as soon as one chain in the domain of the distribution is lockable. Surprisingly, we do not know of any nontrivial regular probability distributions $\mathcal{P}_n^{\Theta,\mathcal{D}}$ that have no lockable chains in their domain. For example, if $\mathcal{D}$ always picks unit edge lengths, and Θ always picks turn angles $\geq \pi/2$, then we do not know whether any lockable equilateral $(\geq \pi/2)$-chains result.

Acknowledgements. Much of this work was completed at the *Workshop on Geometric Aspects of Molecular Reconfiguration* organized by Godfried Toussaint at the Bellairs Research Institute of McGill University in Barbados, February 2002. We appreciate the helpful discussions with the other participants: Greg Aloupis, Prosenjit Bose, David Bremner, Vida Dujmović, Herbert Edelsbrunner, Jeff Erickson, Ferran Hurtado, Henk Meijer, Pat Morin, Mark Overmars, Suneeta Ramaswami, Ileana Streinu, Godfried Toussaint, and especially Yusu Wang.

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