Theoretical Analysis of Geographic Routing in Social Networks

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Abstract

We introduce a formal model for geographic social networks, and introduce the notion of *rank-based friendship*, in which the probability that a person v is a friend of a person u is inversely proportional to the number of people w who live closer to u than v does. We then prove our main theorem, showing that rank-based friendship is a sufficient explanation of the navigability of any geographic social network that adheres to it.

1 A Model of Population Networks

There are two key features that we wish to incorporate into our social-network model: *geography* and *population density*. We will first describe a very general abstract model; in later sections we examine a concrete grid-based instantiation of it.

Definition 1.1 (Population network) *A* population network *is a 5-tuple* $\langle L, d, P, \mathsf{loc}, E\rangle$ *where*

- L *is a finite set of* locations *(*$\ell, s, t, x, y, z, \ldots$*);*
- $d : L \times L \longrightarrow \mathbb{R}^+$ *is an arbitrary* distance function *on the locations;*
- P *is a finite ordered set of* people *(*$u, v, w, \ldots$*);*
- $\mathsf{loc} : P \longrightarrow L$ *is the* location function*, which maps people to the location in which they live; and*
- $E \subseteq P \times P$ *is the set of* friendships *between people in the network.*

The ordering on people is required only to break ties when comparing distances between two people. Let $\mathscr{P}(L)$ denote the power set of L.

Let $\mathsf{pop} : L \longrightarrow \mathbb{Z}^+$ denote the *population* of each point on L, where $\mathsf{pop}(\ell) := |\{u \in P : \mathsf{loc}(u) = \ell\}|$. We overload notation, and let $\mathsf{pop} : \mathscr{P}(L) \longrightarrow \mathbb{Z}^+$ denote the population of a subset of the locations, so that $\mathsf{pop}(L') := \sum_{\ell \in L'} \mathsf{pop}(\ell)$. We will write $n := \mathsf{pop}(L) = |P|$ to denote the total population, and $m := |L|$ to denote the total number of locations in the network.

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Let $\mathsf{density} : L \longrightarrow [0,1]$ be a probability distribution denoting the *population density* of each location $\ell \in L$, so that $\mathsf{density}(\ell) := \mathsf{pop}(\ell)/n$. We similarly extend $\mathsf{density} : \mathscr{P}(L) \longrightarrow [0,1]$ so that $\mathsf{density}(L') = \sum_{\ell \in L'} \mathsf{density}(\ell)$. Thus $\mathsf{density}(L) = 1$.

We extend the distance function to accept both locations and people in its arguments, so that we have the function $d : (P \cup L) \times (P \cup L) \longrightarrow \mathbb{R}^+$ where $d(u, \cdot) := d(\mathsf{loc}(u), \cdot)$ and $d(\cdot, v) := d(\cdot, \mathsf{loc}(v))$ for all people $u, v \in P$.

When comparing the distances between people, we will use the ordering on people to break ties. For people $u, v, v' \in P$, we will write $d(u,v) < d(u,v')$ as shorthand for $\langle d(u,v), v \rangle \prec_{lex} \langle d(u,v'), v' \rangle$. This tie-breaking role is the only purpose of the ordering on people.

2 Rank-Based Friendship

Following the navigable-small-world model of Kleinberg [1, 2], each person in the network will be endowed with one *long-range link*. We diverge from the model of Kleinberg in the definition of our long-range links. Instead of distance, the fundamental quantity upon which we base our model of long-range links is *rank*:

Definition 2.1 (Rank) *For two people $u, v \in P$, the* rank of v with respect to u *is defined as*

$$\mathsf{rank}_u(v) := |\{w \in P : d(u,w) < d(u,v)\}|\,.$$

Note that by breaking ties in distance consistently according to the ordering on P, for any $i \in \{1, \ldots, n\}$ and any person $u \in P$, there is exactly one person v such that $\mathsf{rank}_u(v) = i$. We now define a model for generating a *rank-based* social network using this notion:

Definition 2.2 (Rank-based friendship) *For each person u in the network, we generate one long-range link from u, where*

$$\mathtt{Pr}[u \textit{ links to } v] \propto \frac{1}{\mathsf{rank}_u(v)}.$$

Intuitively, one justification for rank-based friendship is the following: person v will have to compete with all of the more "convenient" candidate friends for person u, i.e., all people w who live closer to u than v does. Note that, for any person u, we have $\sum_v 1/\mathsf{rank}_u(v) = \sum_{i=1}^n 1/i = H_n$, the nth harmonic number. Therefore, by normalizing, we have that

$$\mathtt{Pr}[u \text{ links to } v] = \frac{1}{H_n \cdot \mathsf{rank}_u(v)}. \tag{1}$$

Under rank-based friendship, the probability of a link from u to v depends only on the number of people within distance $d(u,v)$ of u, and not on the geographic distance itself.

One important feature of this model is that it is *independent* of the dimensionality of the space in which people live. For example, in the k-dimensional grid with uniform population density and the L_1 distance on locations, we have that $|\{w : d(u,w) \leq \delta\}| \propto \delta^k$, so the probability that person u links to person v is proportional to $d(u,v)^{-k}$. That is, the rank of a person v with respect to a person u satisfies $\mathsf{rank}_u(v) \approx d(u,v)^k$. Thus, although this model has been defined without explicitly embedding the locations in a metric space, our rank-based formulation gives essentially the same long-distance link probabilities as Kleinberg's model for a uniform-population k-dimensional mesh.

3 Rank-Based Friendship on Meshes

In the following, our interest will lie in population networks that are formed from meshes with arbitrary population densities. Let $L := \{1, \ldots, q\}^k$ denote the points on the k-dimensional mesh, with length q on each side. We write $x = \langle x_1, \ldots, x_k \rangle$ for a location $x \in L$. We will consider Manhattan distance (L_1 distance) on the mesh, so that $d(\langle x_1, \ldots, x_k \rangle, \langle y_1, \ldots, y_k \rangle) := \sum_{i=1}^{k} |x_i - y_i|$. The only restriction that we impose on the people in the network is that $\mathsf{pop}(\ell) > 0$ for every $\ell \in L$—that is, there are no ghost towns with zero population. This assumption will allow us to avoid the issue of disconnected sets in what follows.

Thus a *mesh population network* is fully specified by the dimensionality k, the side length q, the population P (with an ordering to break ties in interpersonal distances), the friendship set E, and the location function $\mathsf{loc} : P \longrightarrow \{1, \ldots, q\}^k$, where for every location $\ell \in \{1, \ldots, q\}^k$, there exists a person $u_\ell \in P$ such that $\mathsf{loc}(u_\ell) = \ell$.

Following the Kleinberg's model of navigable small worlds, we include *local links* in E for each person in the network. For now, we assume that each person u at location $\ell^{(u)} = \mathsf{loc}(u)$ in the network has a local link to some person at the mesh point in each cardinal direction from $\ell^{(u)}$, i.e., to some person at each of the $2k$ points $\langle \ell_1^{(u)}, \ldots, \ell_{i-1}^{(u)}, \ell_i^{(u)} \pm 1, \ell_{i+1}^{(u)}, \ldots, \ell_k^{(u)} \rangle$, for any coordinate $i \in \{1, \ldots, k\}$. Thus, for any two people u and v, there exists a path of length at most qk between them, and, more specifically, the geographically greedy algorithm will find a path of length no longer than qk.

In a *rank-based mesh population network*, we add one long-range link to E per person in P, where that link is chosen probabilistically by rank, according to (1).

4 The Two-Dimensional Grid

For concreteness, we focus on the two-dimensional grid, where we have $L := \{1, \ldots, q\} \times \{1, \ldots, q\}$, and thus $m = |L| = q^2$. We may think of the two-dimensional grid as representing the intersection of integral lines of longitude and latitude, for example.

In this section, we will show that the geographically greedy algorithm on the two-dimensional grid produces paths that are on average very short—more precisely, that the expected length of the path found by the geographically greedy algorithm is bounded by $O(\log^3 n)$ when the target is chosen randomly from the population P. Formally, the geographically greedy algorithm $\mathsf{GeoGreedy}$ proceeds as follows: given a target t and a current message-holder u, person u examines her set of friends, and forwards the message to the friend v of u who is geographically closest to the target t. First, we need a few definitions:

Definition 4.1 (L_1-Ball) *For any location $x \in L$ and for any radius $r \geq 0$, let*

$$B_r(x) = \{y \in L : d(x, y) \leq r\} = \{y \in L : |x_1 - y_1| + |x_2 - y_2| \leq r\}$$

denote the L_1-ball of radius r centered at location x.

We consider an exponentially growing set $\mathscr{R} := \{2^i : i \in \{1, 2, 4, \ldots, 128\lceil \log q \rceil\}\}$ of ball radii, and we place a series of increasingly fine-grained collections of balls that cover the grid:

Definition 4.2 (Covering Radius-r Ball Centers) *For any radius $r \in \mathscr{R}$, let the set*

$$\mathscr{C}_r := \{z \in L : 2z_1 \bmod r = 2z_2 \bmod r = 0\}$$

be the set of locations z such that z_i/r is half-integral for $i \in \{1,2\}$.

For each radius $r \in \mathscr{R}$, we will consider the set of radius-r balls centered at each of the locations in $\mathscr{C}_r$. We begin with a few simple facts about these L_1-balls:

Fact 4.3 (Only a small number of balls in $\mathscr{C}_r$ overlap) *For each each radius $r \in \mathscr{R}$:*

1. *For each location $x \in L$, we have that $|\{z \in \mathscr{C}_r : d(z,x) \leq r\}| \leq 25$.*
2. *For each location $z \in \mathscr{C}_r$, we have that $|\{z' \in \mathscr{C}_{r/2} : B_{r/2}(z') \cap B_r(z) \neq \emptyset\}| \leq 169$.*

Proof. For the first claim, note that if $|z_1 - x_1| > r$ or if $|z_2 - x_2| > r$, then $d(z,x) > r$, and z is not an element of the set of relevance. Thus every $z \in \mathscr{C}_r$ such that $d(z,x) \leq r$ must fall into the range $\langle x_1 \pm r, x_2 \pm r\rangle$. There are at most five half-integral values of z/r that can fall into the range $[b, b+2r]$ for any b, so there are at most twenty-five total points $z \in \mathscr{C}_r$ that satisfy $d(x,z) \leq r$.

For the second claim, notice that any ball of radius $r/2$ that has a nonempty intersection with $B_r(z)$ must have its center at a point z' such that $d(z,z') \leq 3r/2$. Thus the only $z' \in \mathscr{C}_{r/2}$ that could be in the set of relevance must have $z'_i \in [z_i - 3r/2, z_i + 3r/2]$ for $i \in \{1,2\}$ and have $2z'_i/(r/2)$ be half-integral. As in the first claim, the number of half-integral values of $2z'/r$ that can fall into the range $[b, b+3r]$ is at most thirteen for any b. Thus there can be at most 169 total points $z' \in \mathscr{C}_{r/2}$ so that $B_{r/2}(z') \cap B_r(z) \neq \emptyset$. □

Fact 4.4 (Relation between balls centered in L and in $\mathscr{C}_r$) *For each location $x \in L$ and for each radius $r \in \mathscr{R}$:*

1. *There exists a location $z \in \mathscr{C}_r$ such that $B_{r/2}(x) \subseteq B_r(z)$.*
2. *There exists a location $z' \in \mathscr{C}_{r/2}$ such that $B_{r/2}(z') \subseteq B_r(x)$ and $x \in B_{r/2}(z')$.*

Proof. For the first claim, let $z \in \mathscr{C}_r$ be the closest point to x in $\mathscr{C}_r$. Note that $x_1 \in [z_1 - r/4, z_1 + r/4]$; otherwise x would be strictly closer to either $\langle z_1 - r/2, z_2\rangle \in \mathscr{C}_r$ or $\langle z_1 + r/2, z_2\rangle \in \mathscr{C}_r$. Similarly we have $x_2 \in [z_2 - r/4, z_2 + r/4]$. Therefore we have $d(x,z) = \sum_{i \in \{1,2\}} |x_i - z_i| \leq r/2$. Let $y \in B_{r/2}(x)$ be arbitrary. Then by the triangle inequality we have $d(z,y) \leq d(z,x) + d(x,y) \leq r/2 + r/2 = r$. Thus we have $y \in B_r(z)$, which proves the claim.

For the second claim, let $z' \in \mathscr{C}_{r/2}$ be the closest point to x in $\mathscr{C}_{r/2}$. By the same argument as above, we have $d(x,z') \leq r/4$. Immediately we have $x \in B_{r/2}(z')$. Let $y \in B_{r/2}(z')$ be arbitrary. Then $d(x,y) \leq d(x,z') + d(z',y) \leq r/4 + r/2 < r$, and $y \in B_r(x)$, which proves the claim. □

Let x and y be two arbitrary locations in L. In what follows, we will use the size of the smallest ball in $\bigcup_{r \in \mathscr{R}} \{B_r(z) : z \in \mathscr{C}_r\}$ that includes both x and y as a ceiling-like proxy for $d(x,y)$, and as the measure of progress towards the target. We will also need a large ball from $\{B_r(z) : z \in \mathscr{C}_r\}$ that includes both x and y and also includes a large ball centered at y.

Definition 4.5 (Minimum enclosing-ball radius) *For any two locations $x, y \in L$, let* $\mathsf{mebr}(x,y)$ *("minimum enclosing-ball radius") denote the minimum $r \in \mathscr{R}$ such that, for some $z \in \mathscr{C}_r$, we have $x, y \in B_r(z)$.*

Fact 4.6 (Relating distance and minimum enclosing-ball radius) *For any $x, y \in L$, let $r :=$* $\mathsf{mebr}(x,y)$. *Then we have $2r \geq d(x,y) \geq r/4$.*

Proof. Let $z \in \mathscr{C}_r$ be such that $x, y \in B_r(z)$, and note that, by definition, there is no $z' \in \mathscr{C}_{r/2}$ such that $x, y \in B_r(z')$. The first direction is easy: by the triangle inequality, we have that $d(x,y) \leq d(x,z) + d(z,y) \leq r + r = 2r$. For the other direction, suppose for a contradiction that $d(x,y) \leq r/4$. Let $z^* \in \mathscr{C}_{r/2}$ be such that $B_{r/4}(x) \subseteq B_{r/2}(z^*)$, as guaranteed by Fact 1. But then we have $x, y \in B_{r/4}(x)$ because $d(x,y) \leq r/4$, which implies that $x, y \in B_{r/2}(z^*)$, which in turn contradicts the minimality of r. □

Thus, in the path from any source $s \in L$ to any target $t \in L$ found by GeoGreedy, the path will always remain inside the ball $B_{d(s,t)}(t) \subseteq B_{2 \cdot \mathsf{mebr}(s,t)}(t)$.

Definition 4.7 (Sixteenfold enclosing ball) *Let $x, y \in L$ be an arbitrary pair of locations, and let $r = \mathsf{mebr}(x,y)$. Let $\mathsf{sebc}(y,r)$ ("sixteenfold enclosing ball center") denote the location $z^*_{y,r} \in \mathscr{C}_{16r}$ such that $B_{8r}(y) \subseteq B_{16r}(z^*_{y,r})$ whose existence is guaranteed by Fact 1.*

Lemma 4.8 (Relationship between ball population and rank) *Let $s, t \in L$ be an arbitrary source/target pair of locations. Let $r = \mathsf{mebr}(s,t)$, and let $z^* = \mathsf{sebc}(t,r)$. Let $x, y \in L$ be arbitrary locations such that $x \in B_{2r}(t)$ and $y \in B_{r/8}(t)$, and let $u, v \in P$ be arbitrary people such that $\mathsf{loc}(u) = x$ and $\mathsf{loc}(v) = y$. Then $\mathsf{rank}_u(v) \leq \mathsf{pop}(B_{16r}(z^*))$.*

Proof. First, we note

$$
\begin{aligned}
d(x,y) &\leq d(x,t) + d(t,y) && \text{triangle inequality} \\
&\leq 2r + r/8 && \text{assumptions that } x \in B_{2r}(t) \text{ and } y \in B_{r/8}(t) \\
&= 17r/8. && (2)
\end{aligned}
$$

We now claim the following:

$$\text{for any location } \ell \in L, \text{ if } d(x,\ell) \leq d(x,y), \text{ then } d(z^*,\ell) \leq 16r. \qquad (3)$$

To prove (3), let ℓ be an arbitrary location so that $d(x,\ell) \leq d(x,y)$. Then we have

$$
\begin{aligned}
d(t,\ell) &\leq d(t,y) + d(y,x) + d(x,\ell) && \text{triangle inequality} \\
&\leq d(t,y) + d(y,x) + d(x,y) && \text{assumption that } d(x,\ell) \leq d(x,y) \\
&\leq r/8 + d(y,x) + d(x,y) && \text{assumption that } y \in B_{r/8}(t) \\
&\leq r/8 + 17r/8 + 17r/8 && (2) \\
&= 35r/8.
\end{aligned}
$$

Then, we have that $\ell \in B_{35r/8}(t) \subseteq B_{8r}(t) \subseteq B_{16r}(z^*)$ by the definition of $z^* = \mathsf{sebc}(t,r)$, which proves (3). Now, by definition of rank, we have that

$$
\begin{aligned}
\mathsf{rank}_u(v) &\leq |\{w \in P : d(u,w) \leq d(u,v)\}| \\
&= \textstyle\sum_{\ell \in L : d(x,\ell) \leq d(x,y)} \mathsf{pop}(\ell) \\
&= \mathsf{pop}(\{\ell \in L : d(x,\ell) \leq d(x,y)\}) \\
&\leq \mathsf{pop}(\{\ell \in L : d(\ell,z^*) \leq 16r\}) \\
&= \mathsf{pop}(B_{16r}(z^*))
\end{aligned}
$$

where the second inequality follows from (3). □

We are now ready to prove the main technical result of this section, namely that the geographically greedy algorithm will halve the distance from the source to the target in a polylogarithmic expected number of steps, for a randomly chosen target person.

Lemma 4.9 (GeoGreedy **halves distance in expected polylogarithmic steps**) *Let $s \in L$ be an arbitrary source location, and let $t \in L$ be a randomly chosen target location, according to the distribution* density$(\cdot)$. *Then the expected number of steps before the geographically greedy algorithm started from location s reaches a point in $B_{d(s,t)/2}(t)$ is $O(\log n \log m) = O(\log^2 n)$, where the expectation is taken over the random choice of t.*

Proof. Let $r_t := \mathsf{mebr}(s,t)$, and let $z_t := \mathsf{sebc}(t, r_t)$ so that

$$z_t \in \mathscr{C}_{16r_t} \text{ and } B_{8r_t}(t) \subseteq B_{16r_t}(z_t). \tag{4}$$

Let z'_t be the location whose existence is guaranteed by Fact 2 such that

$$z'_t \in \mathscr{C}_{r_t/16} \text{ and } B_{r_t/16}(z'_t) \subseteq B_{r_t/8}(t) \text{ and } t \in B_{r_t/16}(z'_t). \tag{5}$$

Putting together (4) and (5), we have the following two facts:

$$B_{r_t/16}(z'_t) \subseteq B_{r_t/8}(t) \subseteq B_{8r_t}(t) \subseteq B_{16r_t}(z_t) \tag{6}$$

$$t \in B_{r_t/16}(z'_t). \tag{7}$$

By Fact 4.6, we know that $d(s,t)/2 \geq r_t/8$. Thus it will suffice to show that the expected number of steps before GeoGreedy started from location s lands in $B_{r_t/8}(t) \subseteq B_{d(s,t)/2}(t)$ is $O(\log n \log m)$.

Suppose that we start GeoGreedy at the source s, and the current point on the path found by the algorithm is some person $u \in P$, at location $x_u = \mathsf{loc}(u)$. By definition, every step of GeoGreedy decreases the distance from the current location to the target t, so we have that

$$d(x_u, t) \leq d(s,t) \leq 2r_t. \tag{8}$$

We refer to a person u as *good* if there exists a long-range link from that person to any person living in the ball $B_{r_t/8}(t)$. Let $\alpha_{u,t}$ denote the probability that a person $u \in P$ living at location $x_u = \mathsf{loc}(u) \in L$ is good. Then

$$\alpha_{u,t} = \sum_{v:\mathsf{loc}(v) \in B_{r_t/8}(t)} \frac{1}{\mathsf{rank}_u(v) \cdot H_n} \geq \sum_{v:\mathsf{loc}(v) \in B_{r_t/8}(t)} \frac{1}{\mathsf{pop}(B_{16r_t}(z_t)) \cdot H_n} = \frac{\mathsf{pop}(B_{r_t/8}(t))}{\mathsf{pop}(B_{16r_t}(z_t)) \cdot H_n}$$

by the definition of good, by Lemma 4.8 (which applies by (8)), and by the definition of pop$(\cdot)$. Noting that the lower bound on $\alpha_{u,t}$ is independent of u, we write

$$\alpha_t := \frac{\mathsf{pop}(B_{r_t/8}(t))}{\mathsf{pop}(B_{16r_t}(z_t)) \cdot H_n} \leq \alpha_{u,t}.$$

Thus the probability that u is good is at least α_t for every person u along the GeoGreedy path. Furthermore, each step of the algorithm brings us to a new node never seen before by the algorithm because the distance to t is strictly decreasing until we reach node t. Thus the probability of finding a good long-range link is independent at each step of the algorithm until it terminates. Therefore, the expected number of steps before we reach a good person (or t itself) is at most $1/\alpha_t$.

We now examine the expected value of $1/\alpha_t$ for a target location $t \in L$ chosen according to the distibution $\mathsf{density}(\cdot)$:

$$\begin{aligned}
\mathsf{E}_{t \in L \sim \mathsf{density}(\cdot)}[1/\alpha_t] &= \sum_t \mathsf{density}(t) \cdot \frac{1}{\alpha_t} \\
&= \sum_t \mathsf{density}(t) \cdot \frac{\mathsf{pop}(B_{16r_t}(z_t)) \cdot H_n}{\mathsf{pop}(B_{r_t/8}(t))} \\
&= H_n \cdot \sum_t \mathsf{density}(t) \cdot \frac{\mathsf{density}(B_{16r_t}(z_t))}{\mathsf{density}(B_{r_t/8}(t))} \\
&\leq H_n \cdot \sum_t \mathsf{density}(t) \cdot \frac{\mathsf{density}(B_{16r_t}(z_t))}{\mathsf{density}(B_{r_t/16}(z_t'))}.
\end{aligned}$$

The equalities follow the definition of expectation, the definition of α_t, and from the fact that $\mathsf{density}(\cdot) = \mathsf{pop}(\cdot)/n$. The inequality follows from the definition of z_t' in (5), using the fact that $B_{r_t/16}(z_t') \subseteq B_{r_t/8}(t)$ and the monotonicity of $\mathsf{density}(\cdot)$.

We now reindex the summation to be over radii and ball centers rather than over targets t. Recall that $z_t \in \mathscr{C}_{16r_t}$ and $z_t' \in \mathscr{C}_{r_t/16}$, and that $B_{r_t/16}(z_t') \subseteq B_{16r_t}(z_t)$ by (6), and therefore that $z_t' \in B_{16r_t}(z_t)$. Thus, we have that

$$\begin{aligned}
\mathsf{E}_{t \in L \sim \mathsf{density}(\cdot)}[1/\alpha_t] &\leq H_n \cdot \sum_t \mathsf{density}(t) \cdot \frac{\mathsf{density}(B_{16r_t}(z_t))}{\mathsf{density}(B_{r_t/16}(z_t'))} \\
&\leq H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \sum_{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)} \frac{\mathsf{density}(B_{16r}(z))}{\mathsf{density}(B_{r/16}(z'))} \sum_{t : z_t' = z'} \mathsf{density}(t) \\
&\leq H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \sum_{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)} \frac{\mathsf{density}(B_{16r}(z))}{\mathsf{density}(B_{r/16}(z'))} \sum_{t \in B_{r/16}(z')} \mathsf{density}(t)
\end{aligned}$$

where the last inequality follows from (7). But then

$$\begin{aligned}
\mathsf{E}_{t \in L \sim \mathsf{density}(\cdot)}[1/\alpha_t] &\leq H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \sum_{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)} \frac{\mathsf{density}(B_{16r}(z))}{\mathsf{density}(B_{r/16}(z'))} \sum_{t \in B_{r/16}(z')} \mathsf{density}(t) \\
&= H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \sum_{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)} \frac{\mathsf{density}(B_{16r}(z))}{\mathsf{density}(B_{r/16}(z'))} \cdot \mathsf{density}(B_{r/16}(z')) \\
&= H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \sum_{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)} \mathsf{density}(B_{16r}(z)) \\
&= H_n \cdot \sum_{r \in \mathscr{R}} \sum_{z \in \mathscr{C}_{16r}} \mathsf{density}(B_{16r}(z)) \cdot |\{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)\}|.
\end{aligned}$$

Now we are almost done: by applying Fact 2 a constant number of times, we have that

$$|\{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)\}| = O(1). \tag{9}$$

Furthermore, we have $\sum_{z \in \mathscr{C}_{16r}} \mathsf{density}(B_{16r}(z)) \leq 25$: by Fact 1, there are at most twenty-five balls in $\mathscr{C}_r$ that include any particular location, so we are simply summing a probability distribution with some "double counting," but counting each point at most twenty-five times. Thus we have

$$\begin{aligned}
\mathsf{E}_{t\in L\sim \mathsf{density}(\cdot)}[1/\alpha_t] &\le H_n \cdot \sum_{r\in\mathscr{R}} \sum_{z\in\mathscr{C}_{16r}} \mathsf{density}(B_{16r}(z)) \cdot |\{z' \in \mathscr{C}_{r/16} : z' \in B_{16r}(z)\}| \\
&\le H_n \cdot O(1) \cdot \sum_{r\in\mathscr{R}} \sum_{z\in\mathscr{C}_{16r}} \mathsf{density}(B_{16r}(z)) \\
&\le H_n \cdot O(1) \cdot \sum_{r\in\mathscr{R}} 25 \\
&= H_n \cdot O(1) \cdot 25 \cdot |\mathscr{R}| = H_n \cdot O(\log q) = O(\log n \log m).
\end{aligned}$$

because $|\mathscr{R}| = \Theta(\log q) = \Theta(\log m)$. □

In the case of uniform population density, the value of $\alpha_{u,t} = \Omega(1/\log n)$ is independent of s and t, and the greedy algorithm finds an s-t path of length $O(\log^2 n)$ with high probability [1, 2].

Theorem 4.10 (GeoGreedy finds short paths in all 2-D meshes) *For any 2-dimensional mesh population network with n people and m locations, the expected length of the search path found by* GeoGreedy *from an arbitrarily chosen source location s and a uniformly chosen target t is $O(\log n \log^2 m) = O(\log^3 n)$.*

Proof. Immediate by inductive application of Lemma 4.8: the expected number of hops required before moving to a node s' with $d(s', t) \le d(s, t)/2$ or t itself is $O(\log n \log m)$; by repeating this process $O(\log(\max_{s,t} d(s, t))) = O(\log qk) = O(\log q^k) = O(\log m)$ times, we must arrive at the target node t itself. □

References

[1] Jon Kleinberg. The small-world phenomenon: An algorithmic perspective. In *Symposium on the Theory of Computation*, volume 32, 2000.

[2] Jon M. Kleinberg. Navigation in a small world. *Nature*, 406:845, 24 August 2000.