Investigating Los Angeles' urban roadway network from a biologically-formed perspective

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The evolution of networks is constrained by spatial properties of the environment; a characterization that is true in both biological and built networks. Hence built networks such as urban streets can be compared to biological networks to reveal differences in efficiency and complexity. This study assessed foraging networks created by the slime-mold *Physarium polycephalum* on proportional 3D-printed topographic maps of metropolitan city of Los Angeles, California. Rapidly-generated isomorphic solutions were found to be consistently and statistically shorter than existing roadways in system length. Slime mold also allocated resources to supporting key nodes, analogous to how heavy traffic flows through major intersections. Further, chemical deterrents inhibited exploration of slime mold in selected areas and allows for testing of network redundancy and system resilience, such as after an earthquake or wildfire.

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14 Abstract

15 The evolution of networks is constrained by spatial properties of the environment; a
16 characterization that is true in both biological and built networks. Hence built networks such as
17 urban streets can be compared to biological networks to reveal differences in efficiency and
18 complexity. This study assessed foraging networks created by the slime-mold *Physarium*
19 *polycephalum* on proportional 3D-printed topographic maps of metropolitan city of Los Angeles,
20 California. Rapidly-generated isomorphic solutions were found to be consistently and
21 statistically shorter than existing roadways in system length. Slime mold also allocated resources
22 to supporting key nodes, analogous to how heavy traffic flows through major intersections.
23 Further, chemical deterrents inhibited exploration of slime mold in selected areas and allows for
24 testing of network redundancy and system resilience, such as after an earthquake or wildfire.

25

26 Introduction

27 Networks are created where paths crisscross one another, forming a collection of nodes in space
28 (Barthelemy 2011). Networks are commonly found across biological and built environments to
29 facilitate transport of materials and information. Cardiovascular systems, neural networks, ant
30 tunnels and termite colonies are all examples of biological transport networks, whereas
31 roadways, power grids, sewage systems, and telecommunications are built infrastructure
32 examples. The evolution of a network and resulting topography are both constrained by spatial
33 properties of the environment; a characterization that is true in both biological and built
34 networks. Hence built networks such as urban streets can be compared to biological networks to
35 reveal differences in efficiency and complexity (Jiang et al. 2008). Urban road networks are
36 essential for the movement of goods, people, and services in metropolitan areas, yet these
37 networks were built over many years that span dynamic economic, political, technological and
38 legal periods that did not inherently promote maximum transit efficiency. Economic drivers may
39 discourage redundancy, yet the availability of multiple pathways allows for the self-healing of
40 networks (Quattrociocchi et al. 2014) and ensures network resilience after disruptions (Tero et al.
41 2010).

42

43 The ways in which urban road networks are constructed has been examined in an assortment of
44 perspectives including through statistics (Samaniego and Moses 2008) and computational
45 modeling (Li et al. 2015). Roadway creating models typically involve advanced mathematical
46 models that may be difficult to interpret (Yang et al., 1998), which may impede many from truly
47 understanding computed designs, including stakeholders who would benefit from a greater
48 understand of network formation. Even when artfully sketched out designs of proposed networks
49 are created, there are limitations in how closely these models may be compared to real-world
50 networks (Jiang 2009). The mathematically designed models can be a crucial first look at
51 roadways particularly for their accuracy and clarity yet having a more tangible and physical
52 model would be beneficial in other ways such as seeing how the network would interact in its
53 environmental surroundings (Samaniego and Moses 2008). Furthermore, translating urban

54 roadway models created mathematically from two-dimensions to three-dimensions are
55 traditionally costly and time consuming to construct, yet provide valuable insight for comparison
56 with real-world networks. A complementary approach to exploring built infrastructure systems is
57 by using biologically created networks, specifically the network-constructing plasmodial slime
58 mold *Physarium polycephalum* (Tero et al. 2010, Adamatzky and Akl 2011, Adamatzky 2014).
59
60 *Physarum polycephalum* is an aceullar, multinucleated ameboid organism that can be observed
61 with the naked eye. In its vegetative stage called plasmodium, *P. polycephalum* explores the
62 environment in search for food (decaying organic matter) using chemotaxis and a contiguous
63 distribution strategy to maximize the area covered. The plasmodium can explore its terrain at a
64 rate up to 5 centimeter per hour (Kessler et al. 1982). Once food is identified, the plasmodium
65 connects to the food by developing a complex and highly optimized network of pulsating veins
66 or tubes. Plasmodium tubes contain actin and myosin as the components to achieve locomotion,
67 shuttle streaming, and transportation of nutrients and chemical signals within the organism (Alt
68 1985). It has been shown repeatedly that *Physarium* exhibits intelligent-like decision making and
69 algebra computing abilities while maintaining the plasmodial network (Nakagaki et al. 2001,
70 Tero et al. 2010, Evangelidis et al. 2017). For example, the plasmodial slime mold has the
71 capability of creating networks isomorphic to that of the Tokyo Railway system, which is highly
72 regarded for its efficiency (Nakagaki et al. 2001, Tero et al. 2010). This is especially impressive
73 given the plasmodial network develops within a few days without any centralized control,
74 whereas the railroad network required years of design and formation effort from civil engineers.
75 What has been lacking in the majority of studies (Adamatzky and Jones 2010, Tero et al. 2010,
76 Adamatzky 2014, Adamatzky et al. 2014) on this plasmodium is that they were conducted on the
77 flat surface in the absence of real-world topographic features such as mountains and valleys that
78 have a dramatic impact on the development of the road networks (but see Adamatzky 2014,
79 Evangelids et al. 2017 as exceptions). Furthermore, slime mold is gravisensitive and positively
80 geotrophic (Moore and Cogoli 1996) meaning in a 3D environment, it will avoid higher
81 elevations and adjust its network structure to accommodate the landscape (Evangelids et al.
82 2017). This biological feature and an increased accessibility of three-dimensional (3D) printing
83 technology makes it possible to investigate the potentially powerful capacity of slime mold as a
84 tool for exploring and potentially re-envisioning urban roadway networks in the cities where
85 prominent geographical features have a strong impact on transportations network development.
86
87 Here we examine how the biological network-building *P. polycephalum* explores the major
88 metropolitan city of Los Angeles, California and compare it to the existing system of freeways.
89 Our study focuses on the downtown Los Angeles region, an area nestled between mountains and
90 foothills, flat basin, and the Los Angeles River, spanning an elevation of 50-500 meters above
91 sea level. The urban roadways and associated traffic patterns of Los Angeles have been the focus
92 of study for decades (Stonex 1957, Teague et al. 1972, Boarnet et al. 1998) and continue to
93 encourage novel thinking in solving congestion and reducing commute times (Wang et al. 2018,

94   Zhou et al. 2018, Gonzalez 2019). As the United States' second largest city and among the most
95   densely populated (US Census Bureau 2015), Los Angeles is widely known for its extensive
96   roadways and congested traffic. Seemingly paradoxically, the combination of Los Angeles'
97   spatial extent and longer road segments contribute to its ranking as the top U.S. city for
98   accessibility to jobs by automobile (Levinson 2012), with higher job accessibility statistically
99   correlated with shorter commute times in the city (Hu 2015).
100
101   This study specifically aims to assess the exploration of the slime mold's foraging on
102   proportional geographic locations of 3D printed topographical maps of Los Angeles. The results
103   from *P. polycephalum*'s exploration will be used to assess the slime mold's ability to generate
104   isomorphic solutions similar to Los Angeles' existing roadway. Slime mold and real-world
105   roadway lengths will be calculated and contrasted to identify which are shorter, thus identify a
106   potentially more efficient network system. This study is not the first to attempt to combine
107   emerging 3D printing technology with network-solving capability of *P. polycephalum* (see
108   Evangelids et al. 2017), yet to our knowledge, it is the first to couple the two to examine applied
109   network design at the scale of a single metropolitan city.
110

Materials & Methods

112   Proportional topographic maps of a 12 km by 15 km area of downtown Los Angeles were
113   captured from Google Earth (Alphabet, California), edited using the Blender (Roosendall, 1998)
114   and MakerBot (Stratasys, New York) software packages and converted into stereolithography
115   files (.stl) using .stl generator software, and printed on a Makerbot 1st Generation Replicator. To
116   have a measurable effect of plasmodium behavior all the elevation values were enhanced 2.5
117   times. 12 cm x 15 cm printed maps (1:100,000 scale) were marked with a dot of permanent paint
118   in fixed locations where the food source (oat flakes) could be placed identically through
119   replicated trials. Seven food source locations were chosen intentionally to align with major
120   intersections of both highways and major roadways in Downtown Los Angeles.
121

122   For each trial each 3D topographic map was placed in a large 20 x 20 cm square petri dish
123   containing an absorbent towel soaked in deionized water. The map, dish, and towel were
124   sanitized for one hour under a UV light to inhibit any fungal growth or contamination. After
125   sanitization, a thin coat of autoclaved non-nutritive 2% agar was painted over the surface of the
126   3D maps. The agar media provided a superior growing surface to bare plastic yet was sufficiently
127   thin enough to not distort scaling of the 3D maps. Agar was allowed to solidify and was then
128   ready for the placement of slime mold and oat flakes at fixed starting locations.
129

130   Plasmodial *P. polycephalum* was cultured into its active form from purchased dry sclerotium
131   (Carolina Biological Supply Company, North Carolina), slime mold's dormant stage. The dry
132   sclerotium was placed in the center of a Petri dish filled with solidified, non-nutritive 2% agar
133   and several oat flakes. The sclerotium was inoculated with deionized water and colonize UV-

134   sterilized oat flakes in a dark and humid 25°C incubator for 48 hours. Three oat flakes inoculated
135   with plasmodial slime mold and four additional sterile oat flakes were placed on fixed locations
136   of the map. The slime mold was incubated at 25°C with no light for 72 hours in a custom-built
137   incubator to allow *P. polycephalum* to fully explore the map and create its network. Preliminary
138   trials revealed 72 hours to be ample time for full exploration of the 3D map by the slime mold.
139   The need for the custom-built incubator came from the objective to take photographs of the
140   entire map at 6-hour intervals over the period of each trial, but without exposing the maps to
141   potential airborne fungal contaminants or to extended periods of light which both alter slime
142   mold growth and behavior. In collaboration with two electrical engineering students at Loyola
143   Marymount University, the incubator was built from off-the-shelf plastic bin and fitted with a
144   Raspberry Pi camera and Graphical User Interface that enabled with a Python Script and an
145   Optical Coherence Tomography System to capture photos of exploration of the slime mold over
146   the map. Full description of the Slime Mold Incubator Camera System (SMICS) is detailed in
147   McGrath et al. 2018 (Figure 1). From the maps generated at the end of the 72-hour exploration
148   period, distances between oat flakes were measured using ImageJ software, and statistical
149   analyses were conducted to compare the plasmodial slime mold's exploration networks with the
150   analogous real-world urban roadway network in downtown Los Angeles (Figure 2).
151

Results

153   Seventeen trials of the plasmodial slime mold's exploration on the proportional 3D topographical
154   maps of the same region of Downtown Los Angeles were conducted (Figure 3). The placement
155   of oat flakes varied only slightly between the study's 17 replicates; however, the difference was
156   not statistically significant (One Way ANOVA, F= 0.04, DF = 2, α = 0.05, p = 0.96). The slime
157   mold's overall exploration on the 3D maps of downtown Los Angeles was found to be shorter
158   than human engineered, pre-existing roadway networks (Figure 4). Slime mold networks were on
159   65.6km ± 13.8km (Average ± Standard Error) of equivalent length shorter than downtown Los
160   Angeles' current urban roadway network. Furthermore, the number of oat flakes explored in
161   each of the maps was suggested to positively affect the efficiency the slime mold had to explore
162   larger distances. Statistical comparisons of the distances between pairs of real-world
163   intersections and matching pairs of oat flakes revealed a significantly shorter pathway was
164   created by the slime mold than that of existing roadways (t-test for two independent groups t =
165   5.37, DF = 218, α = 0.05, p<0.0001).
166

Discussion

168   This study confirms that the plasmodial slime mold *P. polycephalum* can create networks
169   comparable to real-world built networks as described in past 2D map studies (Nakagaki et al.
170   2001, Tero et al. 2010). More so, this study illustrates that when presented with 3D printed maps,
171   specifically those at the city-scale with real-world topographic features, the slime mold identifies
172   pathways that are typically shorter and thus potentially more cost-effective than pre-existing city
173   roadway networks. This is valuable because explorations such as these can reveal not only

174 shorter pathways, but also variables such as network connectivity that if even slightly improved
175 can reduce traffic commute time (Levinson 2012).
176
177 The connectivity of the network provides insight into how paths are organized hierarchically.
178 Jiang (2009) determined that a minority of roadways (20%) handle the majority of traffic (80%),
179 with the top 1% of paths managing 20% of traffic flow. Thus, although the current study focused
180 on a limited number of fixed locations (i.e. a fixed number of oat flake food sources) in the
181 construction of the network, these locations were where major highways and roadways intersect
182 and heavy traffic flows. Importantly, there is a cost associated with the lengths within a network
183 that must span a large area and these lengths can dramatic influence the overall topography of the
184 network (Barthelemy 2011). In an urban area, a single road length may be necessary to connect
185 an isolated neighborhood or industrial facility to the rest of the network, consequently adding to
186 the overall expansion and associated maintenance cost of the roadway network. A limitation of
187 our experimental design was our focus on major roadway intersections and future work may
188 examine such isolated, yet important elements of an urban landscape at a higher resolution, a
189 task shown possible here with our examination using a scaled 3D map of only a 12 km x 15 km
190 area of downtown Los Angeles.
191
192 Observed shorter slime mold pathways than real-world roadways may be influenced by how
193 each network was created. Urban roadways are built over time, often in a non-linear progression
194 with inherent restrictions including land ownership, economic resources, and a wide range of
195 social, political, and historical considerations. Furthermore, the development of real-world
196 roadways may be modeled by preferential attachment (Barabasi and Albert 1999) – the concept
197 that new nodes prefer to link to already well-connected network nodes. In an urban scenario, a
198 new housing or commercial development may preferentially be connected directly to a
199 population center, but at a net cost to the overall efficiency of the roadway network. In contrast,
200 slime mold's exploration follows a minimalist strategy creating the most efficient links while
201 curtailing resource expenditure (Adamatzky and de Oliveira 2011). Slime mold will abandon
202 explored pathways that are no longer the most efficient for its metabolic function (achieved by
203 leaving a non-living mat of transparent extracellular slime) (Reid et al. 2012), whereas urban
204 roadways are not typically decommissioned or removed.
205
206 A high level of network similarity was qualitatively identified among the 17 72-hour iterations.
207 These data suggest there are certain pathways across the landscape that are important to the
208 overall connectivity and efficiency of the network. Recognizing which routes are important
209 allows for resilience testing of the network in the event of a failure (Quattrociocchi et al. 2014),
210 such as in an earthquake, landslide, or anthropogenic disaster. Future studies may playout such
211 scenarios by applying chemical deterrents such as sodium chloride (Adamatzky and de Oliveira
212 2011) or a light beam (Tero et al 2010) to inhibit the exploration of slime mold into disturbed
213 areas, and then identifying the most efficient alternative routes.

214
215 Urbanization will continue in the coming decades with 68% of the world's population predicted
216 to live in cities (United Nations 2018). Urban growth often facilitates economic development
217 but is also typically associated with the undesirable effects of increased traffic congestion and
218 pollution (Quaas and Smulders 2018). The application of emerging, yet appropriate technology
219 may counter these unintended outcomes. For example, although between 1980 and 2000 the
220 greater Los Angeles area grew by more than 40% and total vehicle mileage increased by 88%,
221 ambient air quality including ozone, sulfur dioxide, carbon monoxide and lead all significantly
222 improved with the application of vehicle emission reducing technology (Kahn and Schwartz
223 2008). Likewise, we demonstrate here the potential for 3D printing technology paired with
224 plasmodial slime mold can inform and guide network construction of urban roadways and
225 potentially other infrastructure systems across real-world geographic features.
226

227 **Conclusions**
228 Our data indicate slime mold presented with real-world topographic features can identify
229 pathways shorter than current existing roadway networks, and the reoccurrence of certain links in
230 multiple test iterations identify where key routes are in the urban roadway network. Given the
231 multiple costs and benefits of urban roadway networks and how increased efficiency of networks
232 can amplify the benefits, we argue for broader inclusion of biologically-inspired design,
233 including the above described inexpensive and rapid approach of coupling slime mold and 3D
234 print technology, in urban roadway discussions and planning.
235

236 **Acknowledgements**
237 The authors thank Daniel McGrath and Stephen Board of the LMU Department of Electrical
238 Engineering and Computer Science for the tremendous contribution in developing the SCIMS
239 system for photo-documenting the growth and behavior of the slime mold. Thanks also to Dr.
240 Michelle Yeung for technical support in printing the 3D maps, and the LMU Summer
241 Undergraduate Research Program for early support of S.D. D.W. thanks Dr. Marga Joaquin for
242 logistical support.
243

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318

Figure 1

Photograph of custom-built Slime Mold Incubator Camera System

Photograph of the custom-designed and built Slime Mold Incubator Camera System (SMICS) used to capture the exploration of the slime mold over the 3D printed maps with one of the 12 cm x 15 cm maps included for scale.

Figure 2

Slime mold data generation sequence from real-world map to processed data.

Slime mold data generation sequence including (A) real-world aerial map with selected intersections of major roadways (red circles), (B) printed 3D map with topographic features and fixed locations (black dots), (C) representative 3D map with inoculated oat flakes at fixed locations, (D) resulting slime mold network (yellow threads) after 3-day incubation, (E) ImageJ software visualizing network connections, and (F) example length measurement of both freeform and direct distance between nodes using ImageJ tool.
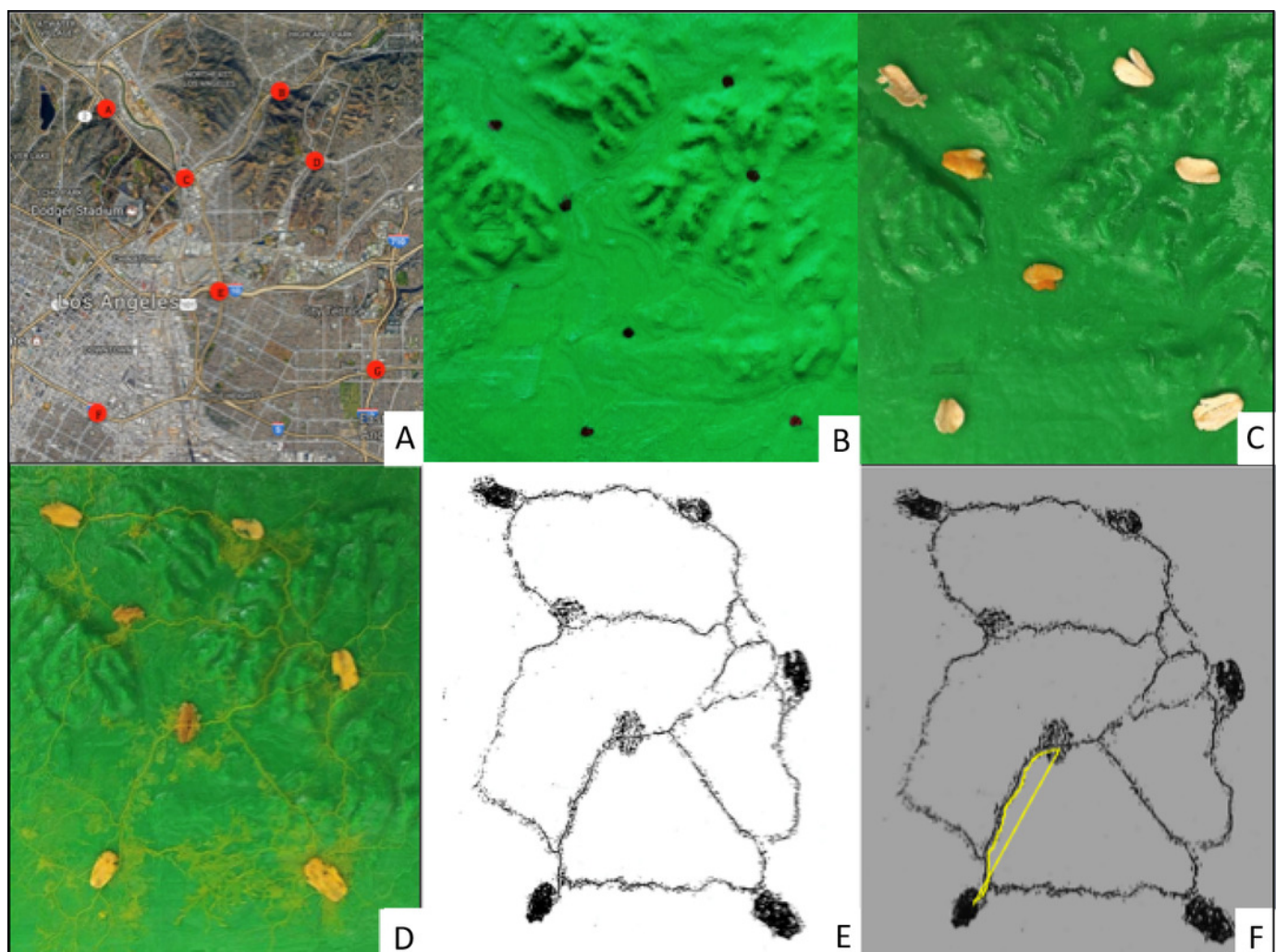
Figure 3

Comparison of slime mold exploration and existing road network

Visual representation comparing the networks of the existing highway and road networks (A) to those that were created by the slime mold's exploration (B). This image also depicts the locations of the nodes of where the food sources (oat flakes) were placed on the 3D printed maps of Downtown Los Angeles. Image area approximately 12 km by 15 km. Map data © 2018 Google .
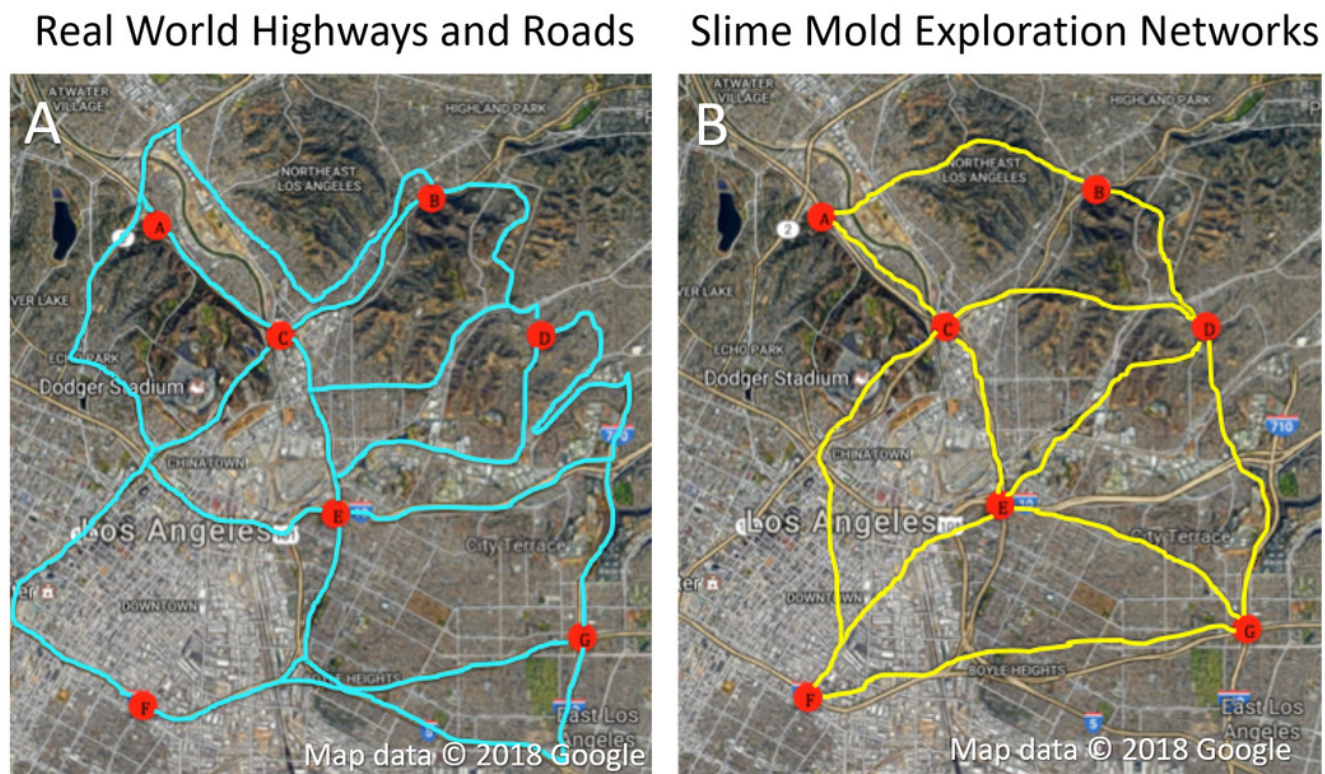
Figure 4

Calculated differences between slime mold and existing road network distances.

Difference in distance of the slime mold's entire exploration on 3D printed maps compared to that of existing highway networks.