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Analysis of the New York Subway System using an Adaptive Network Model

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ABSTRACT

Through the use of a *Physarum Polycephalum* organism and a scaled-down model of the New York Subway System, this study created and analyzed a system of "maximum efficiency". By taking advantage of the capabilities of a Physarum organism, a system reminiscent of the existing subway system was created, with deviations analyzed to find differences in both track usage and overall costs. Previous research regarding *Physarum Polycephalum* and infrastructure development were relatively separate. This study holds similarities to research done by Atsushi Tero of Kyoto University, but while his team sought perfect replication, this study sought to use the growth patterns of *Physarum* to create a more efficient system. Using a geographically accurate mapping of the New York Subway System, a scaled-down model of the Subway System was created, with major subway stations represented as oat nodes atop an agar solution in a sterile petri dish. The *Physarum* was placed within and allowed to grow for roughly 6 days. Following the full connection of all oat nodes, an analysis of the *Physarum* system was conducted using a ModaCam system. This analyzed system was then scaled up to that of the existing Subway System, and a comparison of the two was conducted. This study concluded that the *Physarum* system was significantly more efficient than the existing system, using fewer subway tracks and consequentially a lower maintenance cost.

Introduction

Transportation infrastructure plays a vital role in our daily lives, supporting the interconnected society we participate in. Despite this importance, it serves a background role, only brought into the limelight when failures are examined. Thus, a cultural zeitgeist built upon animosity brings about constant complaints of infrastructure, from electrical outages, heavy traffic, or late trains. In the United States, these complaints are often warranted. For example, in 2022, roughly 1 in 5 trains of the New York Subway System arrived at their station behind schedule, a statistic that has worsened since 2020 (MTA Performance Dashboard, 2022).

While sufficient research has been conducted on infrastructure inefficiency, such as how it is caused, there has been a noticeable lack in research into possible systems or changes to current infrastructure. Such research requires a hypothetical situation, one where political and economic barriers would be put to the side in order to come up with a model of maximum efficiency. These models would serve as a point of comparison, imparting a greater understanding of current systems through knowing their fullest potential. Such maximum efficiency models may be achieved by a surprising organism, the *Physarum Polycephalum*, more commonly known as “Slime Mold.” The star of a viral Japanese study on infrastructure, *Physarum* has the unique ability to maximize surface area in order to obtain sustenance, while minimizing excess “slime” that would otherwise consume energy (Atsushi Tero et al, 2010). This incredible ability allows the once hypothetical system to be brought to reality, wherein placing the slime under similar conditions of an infrastructure system can lead to a replication of said system.

In this study, a *Physarum Polycephalum* organism will be enticed to create a model of the New York Subway System, a vital component of the United States’ infrastructure. Although often scrutinized, the New York Subway provides transportation across the city, having served 750 million passengers in 2021 alone (MTA Info, 2022). The vitality of the system is best expressed through an analysis of the area it serves, the New York metropolitan area. With a GDP of 1.8 trillion dollars, the metropolitan's economic output is comparable to that of Canada, and the density of its location requires a robust transportation system (Perry, 2019). Despite this, the subway system has a massive maintenance cost, with a 2018 budget of 16.6 billion dollars boiling down to a car-mile cost of $14.55, the cost to move a single railcar one mile. For comparison, the Chicago Train Authority cost per car-mile of the same year was only $8.41 (Harris, 2020).

Deviations from the current system may reveal where outside factors affected the subway system. In this way, the single-minded goal of growth plays into the *Physarum's* favor, leaving it unaffected by the politics, costs, or laws. These aspects of infrastructure, while hindering the possibilities, also reveal societal values and expectations, concepts that any engineer must consider. By comparing a system tethered to these concepts to one that is not, a quantitative value of these values may be determined. These numbers can be further used as a benchmark for development, comparing a system of maximum efficiency to the achievements of society, and learning where to improve.

Literature Review

Much of the research relating to the topic of *Physarum* and infrastructure focuses on only one of the two sides. The slime mold is a celebrity in the research world, being used in applications from biology to artificial intelligence. Thus, a portfolio of examinations on the behaviors of *Physarum* can easily be found. On the other hand, infrastructure research analyzes infrastructure systems as well as the political agendas and fiscal policies that affect them. The relationship between the two and how one may affect the other is a field that has been heavily researched. However, a connection between the *Physarum* and infrastructure has not been established. Applying the characteristics unique to *Physarum Polycephalum* could lead to the establishment of a new facet of research and connect both fields together.

The infrastructure employment possibilities of *Physarum* were initially explored by Atsushi Tero, associate professor at Kyushu University. In this research, Tero and his team used the slime mold to develop a complex *Physarum* system, dubbed as a "biologically inspired model for adaptive network development" (Tero et al., 2010). Using food sources to represent train stations and bright lights to represent constraints, the slime mold developed a network reminiscent of the existing Tokyo rail network. More importantly, the calculated characteristics of the *Physarum* network were comparable in cost, transportation efficiency, and fault tolerance to existing systems. While the study proved the success of the *Physarum* model in replicating the desired infrastructure system, it lacked any significant information on differentiations between the two systems. In essence, the research sought a mirrored system, not an improved one. However, it did hint at the possibility of a comparison, stating that the model's multiple parameters make adjustments and the analysis of such differentiations possible.

The unique characteristics of *Physarum* are further explored in an investigation of its spatial awareness (Reid et al., 2012). As the plasmodium forages for food, it leaves behind an extracellular gray slime on areas it already occupied. This slime serves as a marking to both researchers and the slime itself on areas it had already occupied. Further, the slime is used as a marking to develop more complex Physarum systems, proven in its ability to explore complex mazes and develop a system most efficient in resource consumption. The ability of the *Physarum* to grow in complex forms while also maximizing space and resources make it the perfect organism to apply to "efficiency" research.

While research on inefficient transportation systems is lacking, there is a significant pool of information as to why these inefficiencies occur in the first place. Joseph W. Westphal, former Under Secretary of the Army, attributes these inefficiencies to politics (2008). In this research, findings concluded that variables as disconnected as political term length and party volatility played massive roles in how a state spends and uses its money on infrastructure. Analyzing national infrastructure, Westphal finds that there are three stages of project development: planning, funding mechanisms, and decision making. Referencing the infrastructure failures following Hurricane Katrina, he states that politically-based decision making undermines infrastructure, and enhances the vulnerabilities of all stages of project development. These statements are further supported and substantiated by the work of Mark Crain and Lisa

Oakley. Professor of Political Economy at Lafayette College, Crain attributes infrastructure inefficiency to funds mismanagement, political agendas, and institutional decisions (1995). This can be further explained by the alleged use of fiscal policy as a political instrument, in which gaudy and recognizable infrastructure projects are put ahead of more stable, long term investments. While these papers analyze specific root causes of infrastructural deficiencies, their focus is on analyses of current systems, not comparisons between them.

It can be accepted without a doubt that politics plays a role in infrastructure, but anthropological literature dictates that society, and the many factors that compose it, are what shape infrastructure (Larkin, 2013). This research also provides a definition for infrastructure, labeling it as "built networks that facilitate the flow of goods, people, or ideas and allow for their exchange over space" (Larkin, 2013). It further suggests that society and the infrastructure it is built upon are inseparable, and that the quirks or deficiencies of one can be caused by or seen in the other. Thus, it can be concluded that attributing infrastructure inefficiency to human nature accounts for every factor that may negatively affect efficiency, and can be used as a catch all term when explaining why infrastructure may be subpar. Therefore, for the sake of simplicity, any deviations from maximum efficiency produced by the results of this project will be attributed to human nature in general.

Efficiency in the transportation setting has been widely discussed, with numerous definitions being used. However, as discussed by researcher Chi-Hong Tsai, these definitions can be boiled down to a comparison of total service output to service inputs (Tsai et al., 2015). This would be represented in a general comparison between distance traveled or hours run to the operating costs required to fulfill them. Other Key Performance Indicators, acronymed as KPIs, include labor and fuel consumption, population density of an area, patronage, and maintenance costs. These KPIs would serve as the variables to be tested, and would be the major figures determining the efficiency of a system. The research conducted by Tsai compared the efficiency of various international rail systems, and in consideration of the capabilities of the Physarum, the KPIs of this experiment will be miles of track used and the subsequent car mile costs to travel throughout the system.

New York City and the vital transportation infrastructure that supports it provides a wholly unique system to analyze. According to David King of Columbia University, the nature of the rapid growth of the city meant that the subway system developed along with it, with new tracks added according to the needs of the people (King, 2011). This "build as you go" mindset may be considered successful, but it also meant a significant lack of foresight or consideration for the overall subway system as development went on. Furthermore, this mindset may be considered more susceptible to the factors outlined previously, with political and economic agendas affecting the development of sections of the subway as time went on. Thus, an analysis of the New York City subway system would expose how these agendas, and the mindset that created the system, affected the final product still used today.

Methodology

Precedents and Reasoning

The experiment and its steps are straightforward, as many of the variables rely on existing systems, thus simplifying replication of the current system to a smaller scale. This emphasis on scale is vital to the main goal of the experiment and will allow smooth translation of quantitative variables between both scaled models. There is precedence for this, with many of the basic procedures used in this translation and replication used previously to create a replication of the Tokyo rail system (Tero et al., 2010). One such example of such procedures is the way in which constraints will be added to the *Physarum*. Replication of geographical and logical constraints can be done through light intensity levels or salt, which are both disliked by the *Physarum*, which will respond by limiting interaction with the area. This experiment differs in the restrictiveness of these constraints, with greater leniency in how the *Physarum* may interact with its environment, as while Tero's experiment sought a system of high congruence, this experiment seeks a replicated system with notable differences.

Justification of Experimentation and Constraints

The nature of this experiment requires multiple factors to be considered and judged. However, a basic overview of the system is a scale mapping of the New York subway system, with light or salt levels dictating the geographical constraints of the *Physarum*, and oats serving as places of interest, such as subway stations and stops. The use of a modacam to measure the lengths of the *Physarum* slime can allow such measurements to be accurately scaled up and compared to the existing system. Changes to routes can then be determined, and a model of visual congruence can be created, displaying the "eyeball" differences between the scale and existing model.

To replicate the subway system, an accurate map will be placed under the *Physarum*, which will be allowed to grow on top of it. The map in question is one of the most important aspects of the experiment, and while the subway map serves as an iconic aspect of the city, it is not inherently accurate (Fig. 1, MTA).

Figure 1. MTA NYC System Map

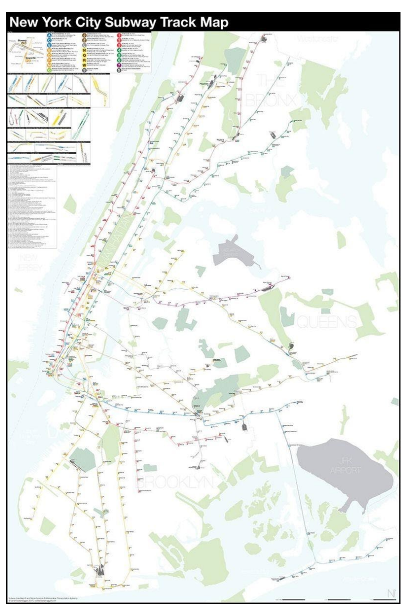


Figure 2. Geographically accurate mapping of the MTA Subway System

The map seen in subway stations and Google searches was developed to simplify the subway riding process, and thus makes use of straight lines and sharp curves that do not accurately represent the subway system, but make the riding experience easier to understand. A more accurate depiction of the subway system was developed by Andrew Lynch, a photographer and cartographer based in NYC. The map was developed through a mix of existing historical maps, satellite imagery, personal observations, and testimonies of retired subway workers (Fig 2, vanshnookenraggen). Unfortunately, the complexity of the subway system, the size of the city itself, and the lack of requests for an official map means that it is unlikely for the MTA to make an official, accurate representation of the subway. Thus, the comprehensive nature of Lynch's model combined with the lack of an official map make the choice simple, and so the vanshnookenraggen map was chosen as the representation of the subway system in this experiment.

The main constraints implemented in this project are geographical in nature. A system of maximum efficiency would disregard economic costs and existing building codes but would consider geographical constraints. For the system, it was decided that the most obvious constraint would be the Hudson River on the West, and the East River in the East. While more restrictive measures could be used, the nature of oat placement meant that slime mold interactions with these constraints was unlikely, and thus these measures were not enacted. The second constraint would be Central Park itself, which in the current system remains untouched, and will be enacted through low levels of fine sea salt. Finally, while Staten Island remains relatively detached from the rest of the subway system, the Staten Island Railway falls under the jurisdiction of the MTA. Thus, the decision was made to neglect prompting the *Physarum* to replicate this line, as such replication would require a second *Physarum*. Besides these two geographical constraints and the unique nature of Staten Island, the *Physarum* will be left free to expand and connect. Further, these constraints will be counteracted by enticing the slime mold via oats, which will represent major subway stations and points of interest.

Physical Experimentation

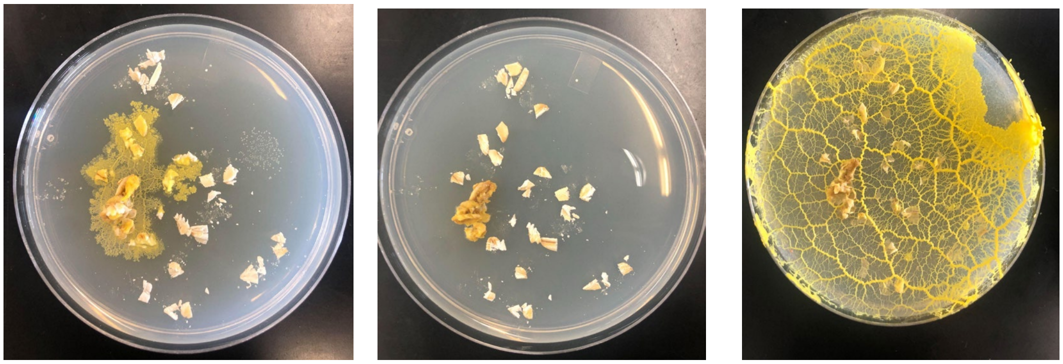
The physical experiment will be centralized to a singular location, in this case being the petri dish the *Physarum* is stored in. Within the petri dish will be the agar medium, oats representing stations, and salt representing the geographical constraints. Physarum will remain untouched, except for watering and data collection at set time periods. The petri dish will be left in a damp, dark location to maximize slime mold growth.

By printing out the scaled map detailed previously, scaling it further to fit within the petri dish can be done by finding the coordinates of stations relative to the map and scaling it down. For example, the printed map has an area of 286cm^2, while that of the petri dish has an area of 33.825cm^2. A station found on the printed map with the coordinates (0.9cm, 5.2cm) can be scaled down to the coordinates of (0.26cm, 1.4cm). Attached to the right are the coordinates of all 39 selected stations and their scaled down counterparts (Fig. 1).

Once the *Physarum* has maximized growth, determined when it encompasses the majority of the petri dish, lengths of *Physarum* can be determined through the use of a ModaCam system, in which precise measurements of the *Physarum* can be made. These can then be scaled up to the size of the map using previously determined measurements, and finally be compared to the features of the geographically accurate map. With a scale of 1cm to 1.2 miles of track, the results of this experiment can be further scaled to the size of the real-world subway system.

Results

The results of the *Physarum* growth were recorded in three separate pictures, roughly two days apart. The final picture was used in further analysis of the *Physarum* system and comparisons with the existing system. *Physarum* figures 3, 4, and 5 are pictures taken of the *Physarum*, with figure 5 being the one used for measurements. Figure 1 was taken after oats were placed and shows that the *Physarum* began growing around the Manhattan area, reminiscent of the existing system. Figure 2 is the *Physarum* in a growth phase, expanding in multiple directions after encountering an oat. This form of growth provides a possible explanation for the results of this experiment, as well as insight into how the existing system may be lacking. Figure 3 is the Physarum having encompassed all oats, and beginning growth outside of the designated petri dish. Larger, more pronounced veins were created between the oats, and represent the major lines connecting subway stations.



Figures 3, 4, and 5. Obtained *Physarum* pictures at different stages of growth

Results were hampered by scaling issues with the ModaCam system, in which it did not provide correctly scaled measurements. However, this issue was solved by determining the scale of the ModaCam numbers to actual numbers through the scale of the Petri dish size. The Petri dish was determined to be 1.6907 cm in diameter, with its actual diameter being 8.75 cm. Thus, a scale of ModaCam to Actual measurements was found to be 5.1753115. This is best understood in the data seen in Student Fig. 6, but the accuracy in scaling leads to the conclusion that this roadblock had no effect on results and their accuracy. To further support this conclusion, hand measurements of the arteries (lines of slime *Physarum*) were made and determined that the measurements in Student Fig. 6 were accurate.

Artery	ModaCam (cm)	Actual (cm)
FL1	0.7825	4.049727925
FL2	0.1106	0.5723960492
FL3	0.5089	2.633746378
FL4	0.5141	2.660658308
FL5	0.535	2.768823565
FL6	0.5118	2.648754955
FL7	0.5012	2.59389602
FL8	0.544	2.815401906
FL9	0.1699	0.8792955584
FL10	0.086	0.4450819189
FL11	0.2265	1.172221565
FL12	0.0667	0.3451972557
FL13	0.1211	0.6267374463
FL14	0.1897	0.9817679072
FL15	0.097	0.5020110016
FL16	0.176	0.9108653224
FL17	0.1837	0.9507156803
FL18	0.0776	0.4016088012
FL19	0.043	0.2225409595
FL20	0.0527	0.2727420596
FL21	0.0476	0.2463476667
FL22	0.1346	0.6966049568
FL23	0.0262	0.1355947241
FL24	0.0683	0.3534778495

Figure 6. X and Y coordinates of model subway stations

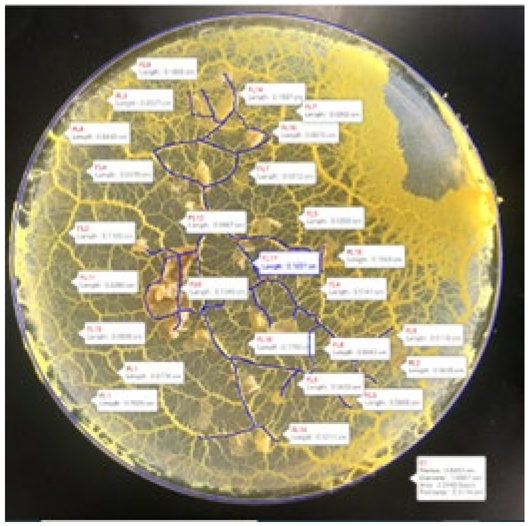


Figure 7. Annotated *Physarum* model

The stage of Physarum used in this experiment is seen below (*Physarum* 1), with post-ModaCam annotations included. Blue lines represent major arteries of the *Physarum*, representing train track routes of its real-world counterpart.

Having scaled up both the measurements of the slime mold and that of the geographically accurate map, a final number of tracks in miles that was used for both models was determined. The *Physarum* model used only 27.67 miles of track, while its real-world counterpart used 117.5 miles, amounting to an approximately 76.4% decrease in miles of track used.

These statistics can be used to further analyze costs in both models to provide a more in-depth understanding. A typical revenue railcar, one carrying paying passengers, consists of 8-10 railcars on average. With a car-mile cost of $14.55, the same cost the New York Subway System operated under in 2018, it would require $13,677 to $17,096.25 to move the average revenue railcar across the entirety of the existing system, not counting for revenue gained from passengers. By comparison, that cost would plunge down to $3220.79 to $4025.99 in the *Physarum* system.

Table 1. Economic effects of the *Physarum* model compared to existing system.

	NYC Subway System (117.5 miles)	***Physarum* System (27.67 miles)**
Cost to travel surveyed system on a $14.55 car-mile cost in dollars	13,677 - 17,096.25	3,220.79 - 4,025.99
Gross revenue on a $10.05 car-mile revenue in dollars	9,447 - 11,808.75	2,224.67 - 2,780.84
Net loss in dollars	4,230 - 5,287.5	996.12 - 1,245.15

Analysis

These results provide a strong response to the research question of this project, showing that there is a significant difference between the existing New York Subway System and one of maximum efficiency. Further, these changes are not limited to minor adjustments in track, but a complete overhaul of how the system is designed. The disparity in track usage efficiency can be explained by several factors. These factors include the constraints of an experiment of this scale, outside factors affecting the existing system, the unique nature of the *Physarum*, and the way in which the New York Subway System was designed and built.

The most important factor that led to the results of this experiment was the constraints of an experiment of this scale. While the scaling up and down remained accurate and consistent, it can be argued that such changes to numbers played a part in the resulting figures. Furthermore, the scale of this experiment necessitated that only a limited number of subway stations were accurately represented, and the inclusion of all existing subway stations would likely lead to a change in results. This could be an idea for future experimentation, but it can be assumed that the *Physarum* would more closely replicate the existing system under those constraints. Finally, human error and outside factors interacting with the *Physarum* during its growth phase may have affected results, which while they could have been mitigated with more trials, was not feasible in the time scale.

The disparity in efficiency and costs demands an examination of both the *Physarum* model and existing system. The *Physarum* model takes advantage of interconnected lines, centralized around Manhattan, reminiscent of the existing system. Furthermore, the *Physarum* grows by branching out from food sources, and later maximizing efficiency by minimizing slime used to connect those sources. In this way, it had knowledge on how to connect these oat nodes best just by encountering them. On the other hand, the existing system was created over a long period of time, often in sections, not through constant growth. Subways and rails were often constructed without understanding where future expansions would be. On top of that, subway stations were built following the laying down of track, opposite to the way the *Physarum* grew. A definite example of this would be the area of Upper Manhattan, where multiple subway lines are diagonal to each other. Instead of replicating this design, the *Physarum* grew one large vein, and branched out from there. This form of growth can be observed throughout the *Physarum* model, more obvious when seen next to the existing subway system.

Conclusion

This experiment was a success, revealing that in terms of track distribution and connection of stations, the existing system is insufficient. In terms of miles of track used, the Physarum model saw a 76.4% decrease in required track, as compared to the existing model. Further, using existing figures on carmile travel costs, this track decrease saw an equivalent decrease in actual travel cost. On a grander scale, the results of the experiment serve to help better understand the value and significance outside factors have on infrastructure, and as a model of how living organisms can be used to further such understanding.

It cannot be denied that the existing system was under much greater and more pressing constraints than its *Physarum* counterpart. However, such a drastic disparity in efficiency reveals just how significant these constraints were. Constantly striving for maximum efficiency in every aspect of infrastructure is not necessarily the best thing overall. For example, an exact replication of the *Physarum* model in the real world might prove less costly per mile, but the damage to existing infrastructure and neighborhoods would be vast. Thus, while it is important to critique all forms of infrastructure, it is just as important to consider the barriers in place that kept them from their fullest potential.

The data from this experiment further solidifies the capabilities of the *Physarum Polycephalum*, both as an organism and as a tool for scientific research. Importantly, this research should not be centralized around the organism itself, and instead expanded to applications of its unique properties. Its capabilities as revealed in this experiment could prove viable in future infrastructure projects, serving as a guide or template for what a system of maximum efficiency would look like. The combination of what is often considered detached studies of science, biology and infrastructure can prove valuable to existing and future projects.

With the data provided from the *Physarum* model and further analysis using real world figures, it can be concluded that the current system of the New York subway system is inefficient in both miles of track used and placement of said track. Further, this inefficiency is of significant concern, with the current system using over 3 times the track used by the *Physarum* model. This information suggests that human factors, such as a lack of planning, played a significant role in the development of the existing system. The results of this experiment serve as both a reminder of the inefficiencies inherent to any system, the unique properties of the subway system development that led to such inefficiencies, and as a display of the capabilities of *Physarum Polycephalum* and its practicality in unique fields.

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