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SOCIAL GROUP MAXIMA: THE BREAKING POINT

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Abstract

What if you were told that your brain would not allow you to have strong relationships with more than 150 people? According to Robin Dunbar, that statement might not be too far off. Dunbar found in a study of primates in their natural environment that the neocortex size (a portion of the brain known as the critical thinking section) correlated well versus mean group size. When this relationship was extrapolated for humans, he found a mean group size of 150. However, how can groups for humans be measured? With conventional definitions containing vague, immeasurable terms, a more usable definition was derived:

“A number of individuals that recognize the names of, have had conversations within the past three months, and share a common goal with one another”

With this definition, a survey study was done on the spring 2010 graduating Chemical Engineers of Penn State University. It was found with 95% certainty that the true mean group size was 15.8 ± 5.1 . This number was much less than Dunbar's quoted number of 150, but it should be noted that his number is a social limit of a human, rather than the size of one single group found in this study.

However, what occurs after the number of 150? In order to test this, a mathematical model was used to simulate the growth of bacteria in a multiple substrate environment. It was hypothesized that when growth parameters were allowed to mutate over time, distinct species would arise. Bacteria growing to a critical population causing speciation would mimic the 'splintering' or breaking of groups after going over the maximum. Running the simulation twice with 10,000

generations showed results that supported our hypothesis, however more testing needs to be done for confirmation.

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Introduction to Group Size

In 1865, a group of six young civil war veterans decided to form a social club. They based their name from the Greek word meaning ‘circle’, shrouded themselves in mystery, held elaborate initiation ceremonies, and played pranks on locals during the night.¹ With such origins, why did the Ku Klux Klan become such a violent super power in American history? Size and timing. The Klan originated in a time of chaos and minimal law. From 1865 to 1867, the KKK grew from its beginning to several ‘Dens’ across Tennessee, Mississippi, and Alabama. At this time, it was decided that the Klan would uphold justice and the constitution in a chaotic post-confederate south.¹ The Klan became a militia group — not uncommon at this time. Many groups rose up to take the law into their own hands such as the Georgia Militia of 1865.² The Klan’s several interpretations of this goal, mixed with general corruption in its ranks, caused the murders, lynching, and violence that they are known for today. Just two years after its founding, Nathan Bedford Forrest, both leader and founder of the Klan, officially ordered the KKK as disbanded. He was quoted as saying the Klan was “perverted from its original purpose”.¹

This is one case in which the size of a social group could have been a source of its downfall. The Ku Klux Klan may have grown so rapidly that the vision of each Den leader clashed. Could the KKK have a different history if they remained small in number? This question is answered by exploring the concept of a social limit or breaking point of group size.

The limit of social group size is not a new concept. Robin Dunbar explored the theory of an maximum group size by studying the brain sizes of primates.³ Dunbar’s theory was popularized by Malcolm Gladwell in his book, *The Tipping Point*, where he uses the study in some of his

social arguments.⁴ Dunbar attempted to find a correlation between the size of a primate brain and various habits — including: distance traveled foraging, percent of fruit in diet, size of territory, and group size. Of these several factors, Dunbar found that the mean group size of several types of primates correlated well to the neocortex size, a specific portion of the brain tied to conscious thought⁵, when standardized to total brain size (as shown in Figure 1). Extrapolating this graph to the range of human’s neocortex ratio (cited by Robin Dunbar as approximately 4:1), he reported that the mean group size of humans was 150.

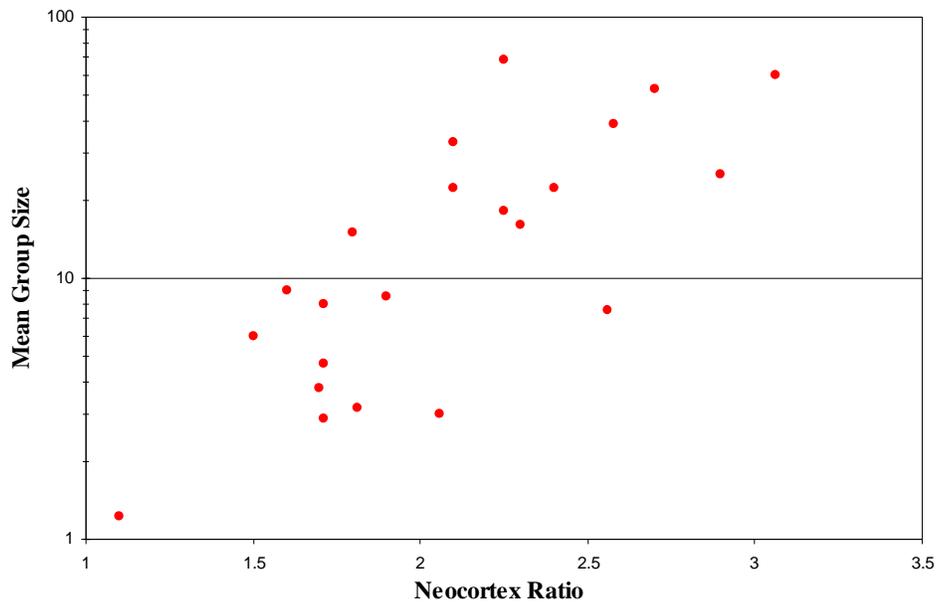


Figure 1. Plot of Dunbar’s Data; mean group size of various primate species on a log scale verses their respective neocortex ratio

Similar to Dunbar’s theory, many other theories exist that question social circle numbers. A network name generator, such as the General Social Survey or Reverse Small World (RSW), can be used to predict average networking sizes for individuals. H. Russell Bernard and colleagues

found in a study using the RSW generator with 6 informants an average of 160 choices of a possible 500 targets. This study was compared to two earlier studies performed with 40 informants with an average of 210 for 1267 targets and 135 for 500 targets.⁶ These studies landed an average network size in the range of 135 – 210; all near Dunbar's number.

So what occurs after passing this social group limit of 150? Dunbar suggested that the *quality* of the relationships suffer. "Their problem, in other words, was not just keeping track of the relationship between Jim and John and themselves, but managing a balance between the three relationships involved. Keeping both John and Jim happy at the same time is a much more difficult feat..."³ One might suggest that after this point, relationships are less valuable and the group would become unstable, thereby disbanding or 'splintering' into smaller groups. This trend can be seen in a study of security agency size by Peter Blau and Richard Schoenherr.⁷ The general trend found was "large agency size generates hierarchical differentiations of authority structure into many managerial levels."⁷ In other words, a larger group size translates into a higher number of distinct smaller groups contained within. The idea of a population growing to a certain level before splitting into distinct groups has been reiterated many times in the subject of speciation. Charles Darwin's book, *The Origin of Species*, contains the beginnings of the concept of speciation.⁸

A difficulty in the exploration or confirmation of this number comes not from the number itself, but the criteria that define group size. Primates such as chimpanzees and gorillas live in communities that are easily counted and large sample sizes can be obtained by observing many different families. As stated by Dunbar, "...it is one of the few things that field-workers invariably count and give solid numerical values for."³ This group definition is more abstract for

humans as they tend to be members of many groups at one time. For Dunbar's studies, grooming was used to define the sizes for primates. In the case of humans, "If modern humans tried to use grooming as the sole means of reinforcing their social bonds, as other primates do, then the equation for monkeys and apes suggests we would have to devote around 40 per cent of our day to mutual mauling," as stated by Dunbar.³ Obviously this is not a sound method to define a group for a human.

Previous studies completed on both the maximum group size (Dunbar), average network size (Bernard), and divisions in companies with large populations (Blau) raise certain questions that will be addressed in this paper:

- **What is a definition of group size that is a measurable quantity for humans?**
- **What are average group sizes using this definition?**
- **At what point does a group grow past the maximum size and splinter into smaller groups?**

Group Size: A Definition

As stated above, Dunbar used a simple definition in defining his group sizes for primates.

Grooming, while sound for primates who live in the wild, is not a sufficient criterion for defining a group of humans. The following are definitions of a social group from Webster's Dictionary and Encyclopedia Britannica, respectively:

“A number of individuals assembled together or having some unifying relationship”

“Any set of human beings who either are, recently have been, or anticipate being in some kind of interrelation.”

While these definitions develop a picture of what a social group is, they do not provide enough structure for measurement. Since social groups cannot be observed and counted in their natural environment (and thereby avoiding any bias), a survey or census must be used. Surveys were chosen as the most practical method of measurement due to the expensive and time consuming nature of a census.

The essence of a survey is to ask the same question to a random sample of a population and compare results. In order for a random sample to be taken, a population needed to be defined. The general social group definitions above cannot be used for this purpose, as it would be very difficult to find all those with unifying relationships. With this in mind, a slightly more distinct definition was purposed:

“A number of individuals that interact with one another and share a common goal”

“Unifying relationship” was refined to “common goal” since a relationship is too ambiguous. Relationships can fall into many categories (personal, romantic, and business) while a goal of a group can be clearly stated.

In a further attempt to reduce the amount of vague, immeasurable terms in the definition for group size, the criteria for what defined an interaction needed to be addressed. The difference between people solely having eye contact with one another or having a deep, emotional

conversation is apparent. These interactions are opposite ends of the social spectrum, so the simplest form of social interaction was used, a conversation, bringing about the definition:

“A number of individuals that recognize the names of, have had conversations, and share a common goal with one another”

In order for members of the simple random sample to accurately answer the survey, a time frame must be given to limit the answers. Otherwise, misinterpretation of the time frame might invalidate the data. For example, “have conversations” could be taken as meaning people you *currently* converse with or those who you have in your *entire life*. These two time blocks are completely different and would yield different survey results. For this definition, the time frame of three months was chosen. Three months is used as the time frame as it was the approximate length of one college semester and, as it will be explained in the next section, this is most relevant for the population chosen for the survey. For the survey as a measurement of average group size, the following is the final definition that was used and it is understood to have strong defined and measurable criteria:

“A number of individuals that recognize the names of, have had conversations within the past three months, and share a common goal with one another”

Experimental Approach: The Survey

A survey was created based on the derived definition for a group, “A number of individuals that recognize the names of, have had conversations within the past three months, and share a common goal with one another.” The population of the simple random sample was chosen:

Population: “Spring 2010 Graduating Chemical Engineering Seniors at Pennsylvania State University”

The common goal in mind was that each student’s goal was to graduate with a B.S. in Chemical Engineering. This population contained 88 students, of which 13 students were randomly chosen and asked to take the survey accounting for 14.7% of the population. The survey (Appendix A) included the following:

Instructions on how to take the survey.

A list of the 88 students in the Spring 2010 Graduating Chemical Engineer Class broken up into 5 sections; two sections of 17 students and three sections of 18 students.

Two questions for the participant to answer. “Please define the group of people listed above” and “Please define the goal/purpose of the group you defined.”

Each person that was asked to take the survey was given a time limit of 5 minutes — 1 minute per section. They were instructed to read each name, decide if they recognize it and have had a conversation with that person in the past three months; if so, they were to mark those names.

After taking the survey, they were instructed to answer the two questions that followed. A histogram of the results can be seen in Figure 2.

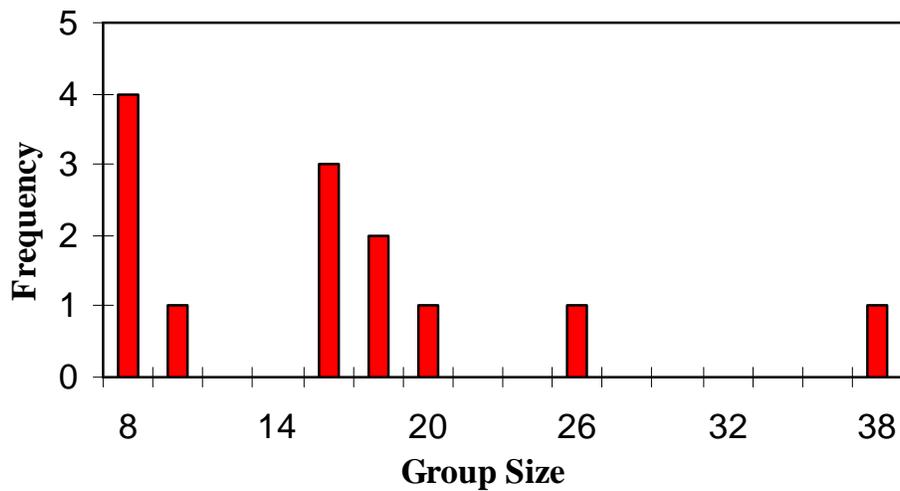


Figure 2. Histogram of the results of the social group size survey. Bins were created in intervals of 2. A mean of 15.8 was found from the data with a 95% confidence interval of 15.8 ± 5.1

Figure 2 shows large groups of students in the group size range of 8 – 10 and 16 – 20 with two data points deviating further towards higher group sizes (26 and 37). Basic statistics were performed on the 13 data points and results showed a mean of 15.8 and a standard deviation of 8.4. It should be noted that a data point in the survey deviated greatly from the bulk of the data (Point 37) as seen on the histogram. Due to the small sample size of 13, excluding a possible outlier has drastic effects on the mean, variance, and confidence interval of the data set. It is for this reason that the outlier was included in the data analysis; however the variation should be noted.

The survey concluded that, with 95% confidence, the true mean for average social group size of the Spring 2010 Graduating Class of Penn State University Chemical Engineers lies between the values of 10.7 and 20.9. This is greatly different from Dunbar’s quoted number of 150. This can

be credited to two reasons: not only did the population size of 88 students limit the study to a maximum group size to a value much lower than 150, but the way in which Dunbar defined his number greatly differed from what was done in this study. “The figure 150 seems to represent the maximum number of individuals with whom we can have a genuinely social relationship...”³ Dunbar’s number is understood as a *social limit* where as this study was designed to find the *average* social group size. “Primates live in small groups where everyone knows everyone else...”³ Primates used in Dunbar’s analysis lived in only one single social group that was counted. Because of this, despite the unit measured for Dunbar’s study being mean group size, it more accurately represented as mean maximum group size. By this definition, Dunbar’s number would suggest that the sum of all social groups an individual is associated with would equal 150 on average.

The data received in this survey would support that claim, as the average group size was found to be a small fraction of 150 and the group defined by the common goal of “Graduating in Spring 2010 from Penn State University with a B.S. in Chemical Engineering” is but one social group that each individual is associated with.

One interesting trend that was also contained in the results from the survey was the correlation between the question answers and the number of checks the individual made on the survey. To reiterate, each of the 13 students were asked the two following questions only after the survey was completed:

“Please define the group of people listed above”

“Please define the goal/purpose of the group you defined.”

Generally, each of the students answered the first question the same; most simply stated “the class of graduating Chemical Engineers” or some deviation with the same meaning. However, the second question where the students were asked to define the goal of the group received answers that depended on the group size each survey taker marked. Those students who marked 10 or less students as the number of students they have had a conversation with in the past three months answered the question as “To complete projects” or another answer with a similar meaning. This was then followed by a break between group sizes of 11 to 15 containing no students in this range. Those who marked higher than 15 answered the question much differently than the students who marked 10 or less, stating the purpose was “To graduate with a degree in Chemical Engineering” or “People who are helping me to graduate.”

These two goals given by the survey participants are very different. Each defines a task that requires a different number of group members. Projects or assignments are traditionally completed by smaller, focused groups that contain a smaller number of participants (usually 3-5 members)⁹ while the general goal of receiving ‘help to graduate’ may require a larger group size.

This trend found in the differences between social group size and the goal that the social group is given validates the derived definition for social group used in the survey. It can be concluded that as the goal of the social group changes, so does the average size of that group.

Groups Beyond the Social Limit: Speciation

Dunbar derived the social limit of 150 and gave many instances in history that supported his claim, such as horticulturalists in Indonesia and the Philippines, small world experiments, the

Church of England, and the British and US army during the Second World War.³ However, instances in which this number was breached were not included. What occurs when a social group attempts to break this social limit? This can be seen in many occurrences today as Fortune 500 companies generally have employee numbers in the thousands rather than hundreds. How do companies beat the social limit of the human brain?

A study was done by Peter Blau and Richard Schoenherr on this specific situation; security agencies ranging from company sizes from the tens to over 9000 employees were analyzed. Several properties of each company were studied, such as occupational positions and managerial levels. In general, “whether local offices, occupational positions, hierarchical levels, functional divisions, or sections per division are considered, size has double effect. It simultaneously increases the number of any of these structural components and their average size.”⁷ It is clear that larger companies are required to break up into smaller subsections in order to function efficiently.

A population growing to a critical size and thereby producing new subgroups also goes by a much different name: Speciation. Charles Darwin discussed in *The Origin of Species* much about his theory of natural selection; the method for which nature causes new species to arise. He concluded that wide-spread areas, which cause large populations, were the best conditions for speciation to occur. “I conclude that for terrestrial productions a large continental area, which has undergone many oscillations of level, will have been the most favourable for the production of many new forms of life, fitted to endure for a long time and to spread widely.”⁸

Both Darwin and Blau concluded, in very different areas of study, that as group size becomes larger, there exists a greater variety in the grouping of the population. What is unclear is at what

size this happens. What is the breaking point for social groups? Many methods are possible for testing this question. Observations of species in nature, analysis of company mergers/hierarchical structure, and mathematical modeling are all possible avenues of exploring the region past the social limit. Because of the time requirement and cost of the two former methods, mathematical modeling was chosen to be investigated in this paper.

Of all possible choices of populations to model and test the limits of maximum population size, bacterial growth is by far the most well documented and studied subject from a kinetic modeling standpoint. It was due to this that it was chosen to model bacteria, specifically *Escherichia coli*, to attempt to attain the size in which speciation occurs.

Analogy with Bacterial Evolution

In 1949, Jacques Monod derived an equation for the modeling of bacterial growth based on empirical data.¹⁰ Monod developed a general model to allow for the modeling of a cell population size over time, being dependent on the amount of substrate in the system^{11, 12, 13}:

$$\mu = \frac{\mu_{max} [S]}{K_m + [S]} \quad (1)$$

Where μ is the overall growth rate, μ_{max} is the maximum growth rate allowable for a given bacteria, S is the substrate concentration, and K_m is the Monod constant. This model allows for

the calculation of population size of any bacteria at any time based on the material balance (eq. 2) and will be the focus of this experiment:

$$\frac{dC_c}{dt} = \mu C_c \quad (2)$$

As shown in Figure 3, bacterial growth contains four main phases¹⁴—a time period in which bacteria adjust to their environment and do not grow quickly (the lag phase), a period of growth that becomes exponentially greater over time (exponential growth), a phase in which the bacteria no longer grow but resist death (stationary phase), and a final phase in which the cells die exponentially (exponential death). In this paper, lag, stationary, and death phases were ignored. Exponential growth will be the only phase that is studied in order to allow for bacteria to reach very large population sizes.

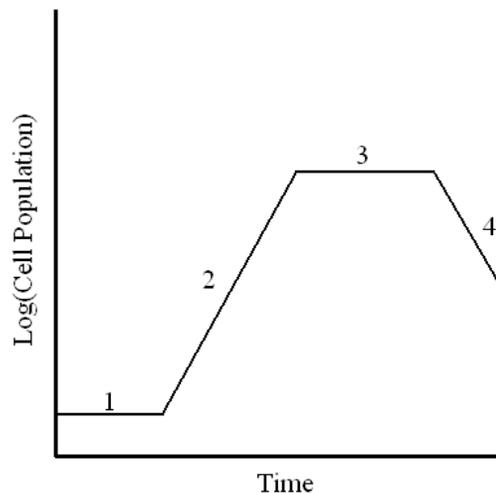


Figure 3. General model of bacterial growth. 1: Lag Phase, 2: Exponential Growth, 3: Stationary Phase, 4: Exponential Death

The following assumptions were made to neglect the other phases of growth:

- Cells are adjusted to their environment
- Unlimited substrate
- No natural cell death

Expanding on the Monod model, several other factors can be included such as how temperature effects alter the value of μ_{\max} ¹⁵, natural cell death^{16, 17}, and environments with multiple substrates¹⁸. For the sake of simplicity, only one of these effects was added into the model: multiple substrates. This would allow for a distribution between cells that mostly preferred one substrate verses another. Multiple substrates were included in the mathematical model based on the following (eq. 3 and 4)¹⁷:

$$\mu = \sum_i \alpha_i \mu_i \quad (3)$$

$$\mu_i = \frac{\mu_{\max,i} [S]_i}{K_{m,i} + [S]_i} \quad (4)$$

Where μ is the overall growth rate, μ_i is the growth rate based on a specific substrate, α_i is a control parameter with values ranging from 0 to 1, $K_{m,i}$ is the Monod constant for a specific substrate, $\mu_{\max,i}$ is the maximum growth rate for a specific substrate, and S_i is the specific substrate concentration. The growth rate, μ_i , is limited by the control parameter, α_i , based on the following:

$$\mu_{max} \geq \sum_i \mu_i \alpha_i \quad (5)$$

The model was allowed to mutate randomly by adding a random Gaussian number (Mean 1, Standard Deviation 0) to each parameter, $\mu_{max, i}$, $K_{m,i}$, based on having 2.5% variation for every two standard deviations of the random number. Each substrate was held constant and therefore was not allowed to change in any way.

Two substrates were utilized in this model; Glucose and Acetone. Values for $\mu_{max, i}$ and $K_{m,i}$ for each substrate can be seen in Table 1:

Table 1. Specific Monod Parameters		
Parameter	Glucose	Acetone
$\mu_{max} (h^{-1})$	0.76	0.32
$K_m (g/L)$	0.04	0.1

A form of natural selection was also integrated into the model. This was done by calculating the overall rate of growth for each cell, by equations 3, 4, and 5, and calculating the number of cells that would be generated for a given time step. Then, the cell population was kept at a constant 2048 cells by randomly choosing 2048 cells from the large amount of cells generated in a given time step. This allowed for the slowly growing cells (low μ) to ‘die out’ by being less likely to be chosen for the next generation.

Under normal conditions, allowing a number to randomize by a Gaussian number will yield a distribution as shown in Figure 4. However, because multiple substrates and a form of natural

selection limit the proposed model, it was the hypothesis that the distribution of growth rate would have a bimodal relationship, rather than unimodal, as shown in Figure 5:

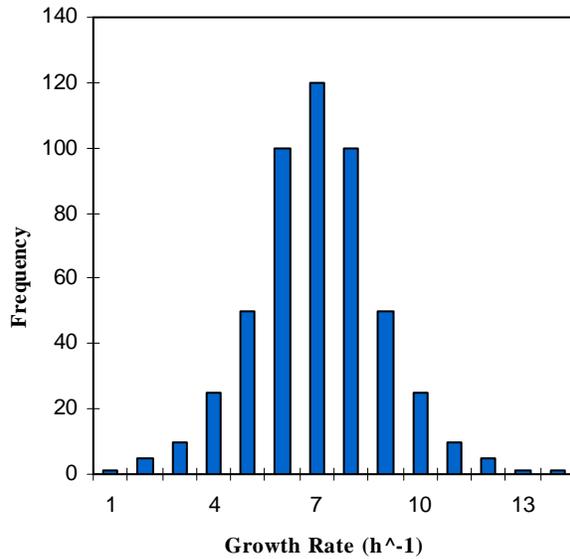


Figure 4. General unimodal distribution.

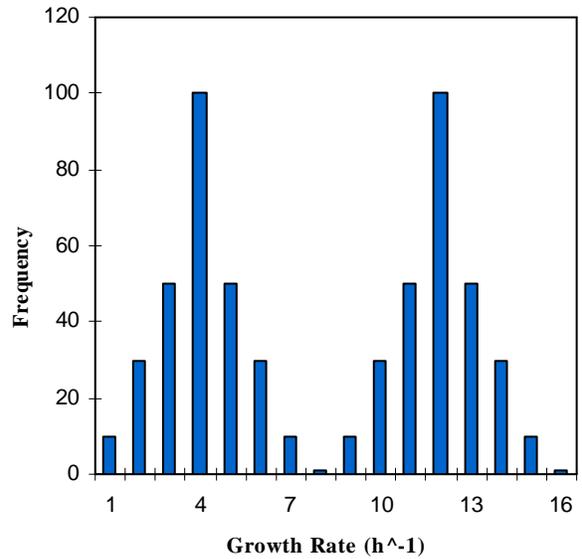


Figure 5. Hypothesis. Bimodal distribution.

Achieving this bimodal distribution is understood as achieving speciation in the population of bacteria, as two distinct populations of bacteria arise with different average growth rates.

Model Approach: The Results

The code for the model can be viewed in Appendix B. *Escherichia coli* was modeled with all cells beginning with the specific substrate parameters listed in Table 1 and with *Escherichia coli*'s μ_{\max} of 0.974 h^{-1} limiting the system by equation 5. Histograms for two separate runs, both

with 10,000 generations and a constant cell population of 2048, can be seen below. A time step of 10 h was chosen for each run and the code took approximately 20 minutes to compile.

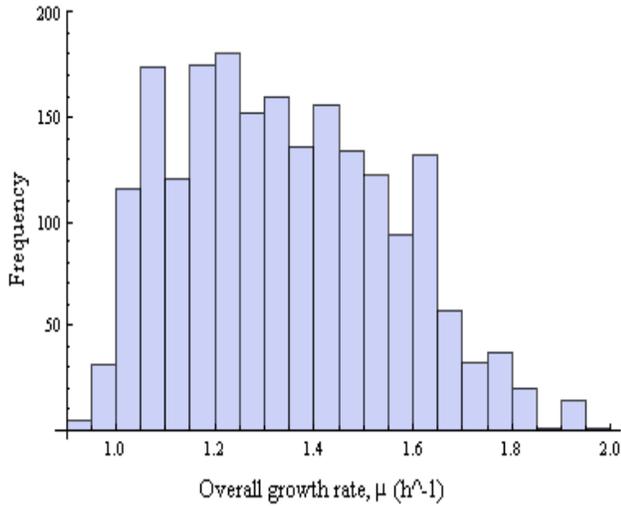


Figure 6. Histogram of overall rate; μ . Run #1, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

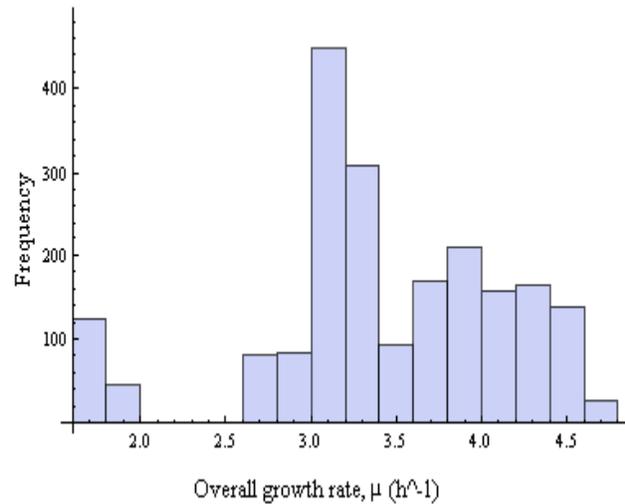


Figure 7. Histogram of overall rate; μ . Run #2, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

Figure 6 and 7 represent histograms of overall rate data for each cell calculated by equation 3 and 4. For this representation, μ was allowed to exceed the μ_{\max} of E Coli (0.974 h^{-1}) in order to reveal any trends mutation. Since each calculated rate is above the threshold of μ_{\max} , a histogram limited by equation 5 would show all cells in a singular bin and offer no real interpretation.

Comparing the two histograms for each separate run of the model, it can be seen that no common trend arises. Figure 6 shows a trend that can be compared to a normal distribution, similar to that of Figure 4, while Figure 7 has several maxima. Due to the overall rate being calculated using the Glucose and Acetone growth rates, it was concluded that viewing how the specific growth

rates changed over time, rather than the overall growth rate, would show clearer trends.

Histograms of these parameters, first being Glucose (μ_1), were generated and can be seen in

Figures 8 and 9.

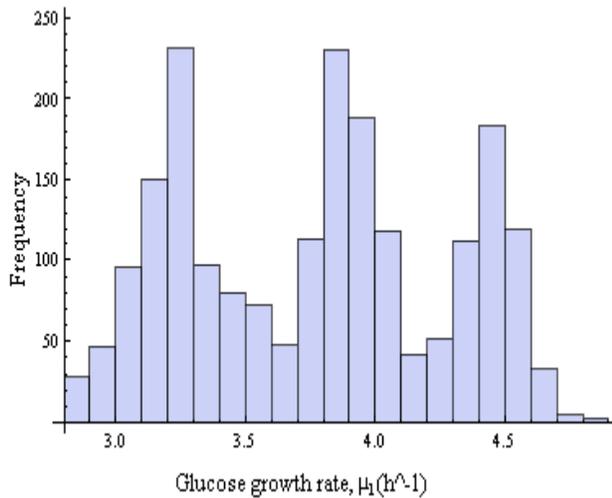


Figure 8. Histogram of Glucose μ_1 . Run #1, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

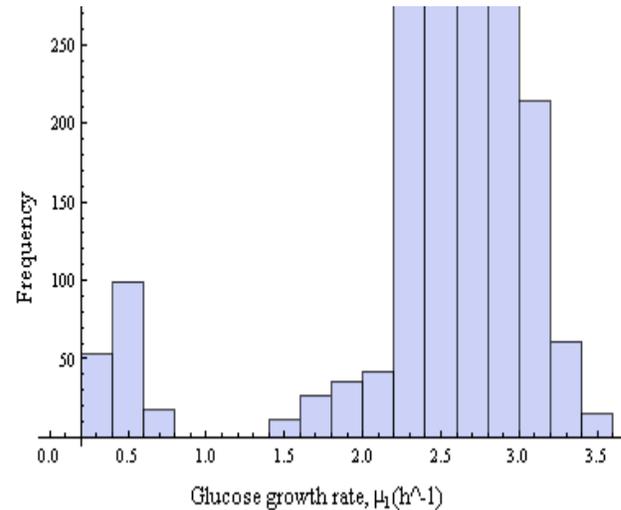


Figure 9. Histogram of Glucose μ_1 . Run #2, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

The results from the Glucose growth rate offer a much better picture of the mutation trend. As seen in Figure 8, Glucose growth rate between cells in Run #1 is inferred to be multimodal. It would appear that three distinct species, with average growth rates of approximately 3.3, 3.9, and 4.5 h⁻¹, existed at the end of the simulation. When compared to the second run, similar trends arise. While Run #2 does not offer the same multimodal trend or growth rates on the same order of magnitude (a range of 2.8–5 in Run #1 compared to 0–3.6 in Run #2) as Run #1, it does show multiple maxima as was shown in the previous run. In order to test the validity of these results, Acetone growth rate (μ_2) histograms were generated for each run as shown in Figure 10 and 11:

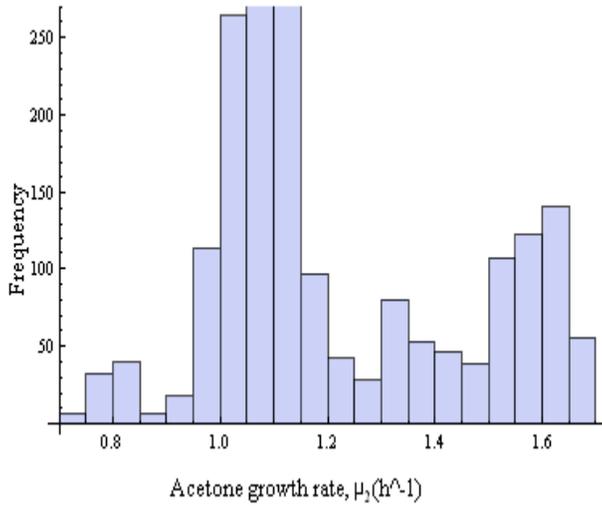


Figure 10. Histogram of Acetone μ_1 . Run #1, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

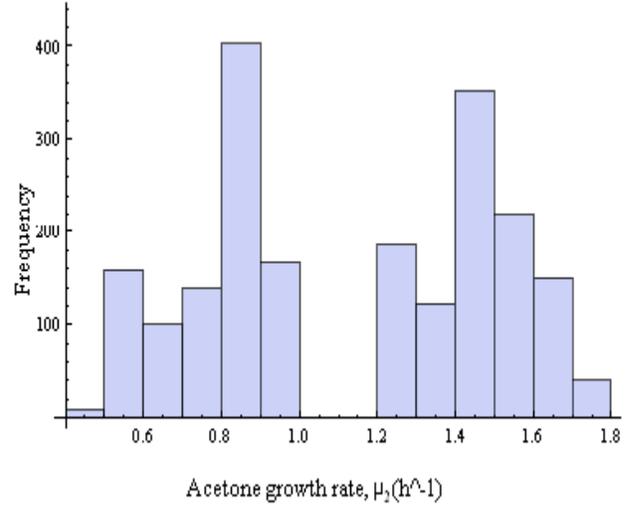


Figure 11. Histogram of Acetone μ_1 . Run #2, 10,000 Gen, 10 h time step, 2048 cells. Bin interval of 0.1

Similar to Glucose, Acetone growth rates showed groupings of the cell population with different maxima. This holds especially true for Figure 11, which contained 0 of the 2048 cells in the 1.0–1.2 range of growth rates.

With the given findings, it can be concluded that for the two runs made with the model, speciation was achieved. The point in which this phenomenon occurred and whether the model follows this general trend for lower cell populations or generations is still under question.

Conclusions and Future Studies

Two different avenues of social dynamics were explored in this paper: The ability to measure group size and the point in which a group ‘splinters’ or speciates. A measurable and unambiguous definition for social group size was derived:

“A number of individuals that recognize the names of, have had conversations within the past three months, and share a common goal with one another”

It was concluded, by using the above definition, with 95% confidence that the true mean of social groups of spring 2010 graduating Chemical Engineers at Penn State University was 15.8 ± 5.1 . This was much different than Dunbar’s quoted ‘150’ as this is just one social group that each student was a member of. It was also found that as the goals of each specific student changed, so did the group size of that student. This finding validated the proposed definition for social group as defined by group members sharing a common goal.

A mathematical model was created that modeled the bacterial growth of *Escherichia coli* under conditions of multiple substrates. Histograms of the results allowed the conclusion that speciation was achieved in this instance; however it cannot be said with certainty that this is always the case.

Alternative experiments and further building of the model can expand on the material presented in this paper greatly. Other possible experiments/expansions include:

- Altering the definition of a social group and observing effects on average group size
- Exploring the concept of group goals defining average group size

- Allowing the model cell population to grow from 1 cell, rather than be limited to a certain number
- Include temperature or death/toxin effects

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Appendix A: Survey Measuring Average Group Size

Chemical Engineering Group Size Survey:

How large is *your* group in the chemical engineering class?

(Provided by Velegol Research Group)

Survey Purpose:

The purpose of this survey is to determine the number of members included within your subgroup of the 2010 Chemical Engineering graduating class. The information obtained in this survey will be used for statistical calculations of average group size. For more information, feel free to contact Justin Murphy (jmm5315@psu.edu) or Didier Greenleaf (ddg5026@psu.edu).

Survey Qualifications:

☛ You will be graduating in Spring 2010 with a degree in ChE. _____ (please check)

Survey Directions:

Spend **one** minute on each section of people (total: five sections). If you recognize a name **and** have had a conversation with this person in the past **three** months, place a check mark on the line provided next to the name.

Afterwards, answer the two short answer questions that are found below.

Note: The administer will inform you when each minute has elapsed

PLEASE FLIP OVER AND PROCEED WITH SURVEY

Additional Questions:

Please classify the group of people you marked on the reverse side.

Please define the goal/purpose of the group you marked

<p style="text-align: center;"><u>Section 1</u></p> <p>____ Viktor Adalsteinsson ____ Benjamin Adams ____ Garrett Adams ____ Hassan Aljama ____ Jacob Ammarell ____ Adam Anderson ____ Jason Baker ____ Amy Bariexca ____ Morgan Barth ____ Christopher Bosenbark ____ Michael Broglie ____ Cammy Brown ____ Colin Brown ____ Dennis Carney ____ Thomas Carpenter ____ Tarick Chaleby ____ Ling Ling Chen</p>	<p style="text-align: center;"><u>Section 2</u></p> <p>____ Christopher Cottle ____ Travis Crouse ____ Lan Dang ____ Jeffrey Decker ____ Steven Derkits ____ Aubrey Dolly ____ Charles Doyno ____ Stephen Eaglen ____ Christopher Ewing ____ Michael Ferrante ____ Shana Ferrante ____ Bridget Finnegan ____ Melinda Gardner ____ Kevin Gasperich ____ Katherine Gawel ____ Erin Golden ____ Eltahir Gotar</p>	<p style="text-align: center;"><u>Section 3</u></p> <p>____ Didier Greenleaf ____ Andrew Gross ____ Benjamin Guyer ____ Fawzi Hamad ____ Daniel Harding ____ Allison Harter ____ Kyle Hartman ____ Robert Hendrix ____ Eric Hoffman-Aho ____ Thomas Hubbard ____ Madhuri Jagadish ____ Megan Karr ____ Brian Keenan ____ Ryan Kelly ____ Stephen Kepics ____ Jeffrey Krug ____ Shaunna Lansberry</p>
<p style="text-align: center;"><u>Section 4</u></p> <p>____ Peter Litwinowicz ____ Michael Macheski ____ Sean Malloy ____ Daniel Marple ____ Derek Maybee ____ McMullen Jamie ____ Nicole Mease ____ David Miller ____ Justin Murphy ____ Ryan Muthard ____ Zachary Muthard ____ Renae Patch ____ Francis Piazza ____ Shane Reid ____ Daniel Rhoads ____ Ralph Romspert ____ Earl Ross ____ Katie Roth ____ Ignacio Russo</p>	<p style="text-align: center;"><u>Section 5</u></p> <p>____ Jeremy Sargent ____ Michael Saville ____ Michael Schriver ____ Taylor Schulz ____ Khayla Shearer ____ William Sheehan ____ Matthew Simon ____ Tamara Siskind ____ Leland Smith ____ Christopher Sokolowski ____ Stephen Spagnol ____ Tyler Speck ____ Paul Squeglia ____ Daulet Torgautov ____ Aimee Tu ____ William Wegemer ____ Corina White ____ Carl Wiesner</p>	

Appendix B: Bacterial Growth Model

(*E coli*)

Generations = 10000; (*Number of generations to perform in simulation*)

keep = 2048; (*Number of cells to be kept between generations*)

store = 100*keep; (*Maximum matrix size for the temp storage of number of cells*)

mult = 1.0; (*Number of time steps allowed*)

t = 10; (*Time step for rate, h*)

$\mu_{max} = .974$;(*Maximum growth rate, limits the substrate growth rates h^{-1} *)

S1 = 1; (*Substrate 1,Glucose. Kept constant*)

S2 = 1; (*Substrate 2,Acetone. Kept constant*)

CellPop=Table[{i,.78,.04,.32,.1},{i,keep}];

(*

Matrix of Cell Population with a constant population of keep.

The matrix is as follows:

{Cell Number, μ for Glucose, Km for Glucose, μ for Acetate, Km for Acetate}

μ are in h^{-1} and Km are in g/L

*)

CellCount = Table[0, {i, store}];

(*Matrix that holds the calculated number of cells for a certain time step mult*)

For[I = 1, i < Generations + 1, i++,

(*Allows the matrix CellPop to iterate for a certain number of defined generations*)

s=Table[{0,RandomReal[NormalDistribution[0,1]]*.013,RandomReal[NormalDistribution[0,1]]*.000666,
RandomReal[NormalDistribution[0,1]]*.005333, RandomReal[NormalDistribution[0,1]]*.001666},{i,1,keep}];

(*Allows each variable in maxtrix CellPop to vary by a value of 2.5% variation for each STD away from the mean of 0 a random Gaussian number is*)

CellPop=CellPop + s; (*alters the values in CellPop by a random amount in s*)

m = 1; (*counter for the maximum number of cells in a time step mult*)

Do[

{If[CellPop[[i, 2]] + CellPop[[i, 4]] < μ_{max} , n = Round[(CellPop[[i, 2]]*S1/(CellPop[[i, 3]] + S1)) + (CellPop[[i, 4]]*S2/(CellPop[[i, 5]] + S2))*t*mult];, n = Round[μ_{max} *t*mult]}

If[n > 0,Do[CellCount[[j]] = i,{j, m, m + n}];

m=m + n;},

{i, 1, keep}];

(*Loop that runs through CellPop, calculating the overall rate of growth based on the Monod model for each cell and storing the number of cells created in a certain time step multi in n*)

rand=RandomInteger[{1, m}, keep]; (*Chooses a random integer keep times from 1 to m*)

rand2=Table[0,{i, 1, keep}];(*Holder for the cell numbers generated by rand*)

Do[rand2[[i]]=CellCount[[rand[[i]]]],[i, 1, keep];(*Runs through CellCount, taking cells out generated randomly by rand and placing them into rand2*)

```
(*Eliminates any kinetic parameters that fall below 0 and sets them to 0*)
Do[If[CellPop[[i, 2]] < 0, CellPop[[i,2]] = 0], {i, 1, keep}];
Do[If[CellPop[[i, 3]] < 0, CellPop[[i,3]] = 0], {i, 1, keep}];
Do[If[CellPop[[i, 4]] < 0, CellPop[[i,4]] = 0], {i, 1, keep}];
Do[If[CellPop[[i, 5]] < 0, CellPop[[i,5]] = 0], {i, 1, keep}];
```

```
CellPop2=Table[{0, 0, 0, 0, 0}, {i, 1, keep}]; (*Temp holder for CellPop*)
```

```
Do[CellPop2[[j]]=CellPop[[rand2[[j]]], {j, 1, keep}]; (*Places all kinetic data from random cells into CellPop2*)
Do[CellPop2[[i,1]]=i, {i, 1, keep}]; (*Resets CellPop2's cell numbers*)
```

```
CellPop = CellPop2; (*Sets CellPop equal to CellPop2*)
```

```
]
```

Curriculum Vitae

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Education

The Pennsylvania State University, State College, PA
Pursuing B.S., Chemical Engineering
Expected Graduation Date: May 2010
Cumulative GPA: 3.64

Experience

Undergraduate Research (August 2009 –Present)

The Pennsylvania State University, Dr. Darrell Velegol's Lab

- Work on research projects in group setting
- Explore the idea of maximum social group size

Supplemental Instructor, Chemistry (January 2008 – Present)

The Pennsylvania State University, University Learning Center

- Lead large-scale student SI sessions to promote critical thinking
- Help students better understand material and concepts
- Attend a previously taken class in Chemistry to increase quality of instructive sessions

Chemistry Tutor (September 2006 – January 2008)

The Pennsylvania State University, University Learning Center

- Helped students struggling in Chemistry to understand material, topics, and concepts
- Mentored small to large groups of students

Skills

Languages

- Proficient Fluency in Spanish

Computer

- Microsoft Word, Excel, Power Point
- MatLab, Mathematica, Hysys, MiniTab, C++, Java, Html

Awards

Schreyer Honors Scholar, The Pennsylvania State University

- Tentatively graduating with Honors in Chemical Engineering