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# WIP: A Visual Approach to Teaching and Learning the Concept of Limit


## Daniel Raviv (Professor)

Daniel Raviv received his B.Sc. and M.Sc. degrees from the Technion, and his Ph.D. from Case Western Reserve University in Cleveland, Ohio. He is a professor at Florida Atlantic University (FAU) where he is the Director of the Innovation and Entrepreneurship Lab. In the past he served as the assistant provost for innovation. Dr. Raviv taught at Johns Hopkins University, the Technion, and the University of Maryland, and was a visiting researcher at the National Institute of Standards and Technology (NIST) as part of a group that developed a vision-based driverless vehicle for the US Army (HUMVEE; 65 mph). His related research work includes exploration of visual invariants that exist only during motion and can be used for real-time closed-loop control systems of cars and drones. He is also interested in teaching and learning innovative thinking, and how to teach innovatively. He is the author of five books: three on learning innovative thinking and two on teaching in visual, intuitive, and engaging ways.

# WIP: A Visual Approach to Teaching and Learning the Concept of Limit

**Daniel Raviv**

**College of Engineering and Computer Science, Florida Atlantic University**

**Emails: ravivd@fau.edu**

**Abstract**

A growing number of students have difficulties connecting mathematical principles to real life. In addition, as technology brings about a paradigm shift in the way people perceive and learn new information, students become more sidetracked, as their attention span has become shorter. They also prefer more visual and intuitive explanations of the material. This suggest that additional teaching methods should be explored to adjust to students' new styles of learning.

This paper describes several illustrative examples aimed at aiding in comprehension of the concept of limit. The idea is to introduce the topic in an intuitive and engaging manner before transitioning to conventional textbook material. Examples are drawn from (1) Art, using examples such as 2d perspective views and vanishing points in images, (2) Physics, using time-related examples such as the tendency towards equilibrium in nature, e.g., approaching temperature and pressure equilibria, (3) Engineering and Technology, using energy related examples such as charging the battery of a mobile phone, (4) Geometry, using images as obtained from two parallel mirrors, and fractals, and (5) Algebra and Calculus, using limit to explain the Golden Ratio, and the concepts of derivative and integration. The paper concludes with related math and engineering brain teasers.

The examples are designed to serve as a *supplemental resource*. The goal is to promote a basic level of intuitive comprehension prior to introducing further mathematical analysis. This will provide students with an easier transition, helping to reinforce intuition to achieve a higher level of success when learning difficult concepts. It is also designed to provide educators with additional material to help engage with students. The information presented is *not meant to replace existing textbook chapters,* or other teaching and learning methodologies.

This paper is a *work in progress.* To *assess* the validity of the proposed approach, the author introduced the concept of limit to students in a Calculus class followed by a detailed questionnaire, resulting in 29 responses. Summary of the results to multiple questions shows a very positive average response. This set of *initial* results indicates that the students preferred being introduced to the concept of limit visually and intuitively. They praised this approach and found it to be very effective for learning. We are working on assessing students’ ability to apply the concept of limits to problems in geometry, trigonometry, and algebra. There is good reason to believe that the approach has a promising potential.

## I. Introduction

Today's students are used to relying less on textbooks and more on web-based resources. These include short videos, animations, blog posts, and so forth. They want math to directly connect with daily experiences and future applications. With shorter attention spans students also expect more immediate explanations of the relevance of the topics they learn. In addition, most mathematical textbooks are loaded with formulas and procedures with little or no connection to daily experiences, causing students to miss the "Eureka" moment – a flash of sudden insight. Many students expect more visual, intuitive, and engaging explanations than educators have traditionally supplied.

Instructors can better serve these students by modifying their approach: first introducing concepts in intuitive and visual ways that are easy to comprehend, and only later digging deeper into textbook derivations and formulas.

This paper introduces the concept of limit through a set of examples that can help students to understand the basic idea behind the topic by visually connecting it to their own experiences, as well as to examples from other disciplines. The examples can be introduced prior to exploring purely mathematical details and are meant to help develop intuition and conceptual understanding of the material. The examples in this paper are meant to be *supplemental* to existing course material for introductory purposes only. The information presented is *not meant to replace existing textbook chapters*, or other teaching and learning methodologies.

The main contribution of this work is to provide students with new visual and intuitive examples that relate textbook explanations to real life scenarios. Instructors can pick and choose examples to supplement their textbook-based teaching to help students in comprehending the material. The paper starts by explaining the concept of limits as it pertains to art. The paper then shifts to other fields such as physics, technology and engineering, and mathematics. It concludes with a set of related brain teasers. It should be noted that in our efforts to effectively communicate the concept we have made some small sacrifices in scientific accuracy and sidestepped more complicated explanations.

*Assessment:* The examples have been shared with students and a questionnaire was used to assess students' thoughts about this teaching approach. Initial results, based on 29 responses that are detailed in the Appendix, indicate that this visual and intuitive teaching method is effective in helping students comprehend the basic idea behind the concept of limit. Students generally felt that understanding the concept of limit was important, as shown in their responses to question 1. They also felt that learning the topic using visual examples (question 2), hands-on activities (question 3), and in-class exercises (questions 4 and 5) was important, while the general opinions on learning through methods such as traditional presentations (question 7) and reading the relevant textbook material (question 8) were more mixed. We plan to present the examples to a larger group of students, and their feedback will be assessed using more rigorous, formative, and summative assessments. Also, we are working on assessing students' ability to apply the concept of limits to problems in geometry, trigonometry, and algebra.

This paper is a *work in progress*. Further study needs to be done to gauge the effectiveness of this work. Soon we plan to present the content of this work to students in Calculus classes. Their feedback will guide the next iteration of our methods. Specifically, students will be asked how much they feel the new presentation has helped their conceptual understanding and their attitude towards math. Ideally, a future class can be designed such that objective measurements can be performed on the effectiveness of these methods using well-known assessment methods, measuring concept comprehension and student interest in the topic. Using a variety of assessment methods should provide a more complete picture of students' learning and proficiency, so we plan to use, at a minimum, individual and group quizzes and tests, authentic performance tasks, observations, and interviews. The most relevant types of assessment in this case are formative and summative (to be focused on student's comprehension).

Extensive attempts have been made to find more effective ways of teaching foundational STEM courses. Trying to find out why so many students struggle with mathematics and what can be done about it shows that there is no one single approach to effective learning [1]. A study of visualization in a freshman Chemistry course showed results that, "suggest that visualization skills do facilitate concept learning, but they do not generalize to higher education in the sciences" [2], which shows that visual approaches are at least helpful for the introduction of new concepts. Studies have also found that visualization improves student motivation in computer science [3], mathematics (see for example [4,5]) and in collaborative online learning environments [6]. Based on similar teaching approach experience that was gained and assessed by the author in other STEM subjects (Control Systems, Digital Signal Processing, Computer Algorithms, Algebra, Calculus, Statics, Thermodynamics, Statistics, and Physics), it is believed that the approach has promising potential.

## II. Examples

### 1. Art

**Vanishing Point**

Imagine that you are standing in the middle of a street. One side is lined with houses and the other side is lined with trees as far as the eye can see (Figure 1). The lines that connect the houses and trees converge at the vanishing point. This point is located at the horizon at which the perceived size of all objects becomes zero, the limit of how far you can see.

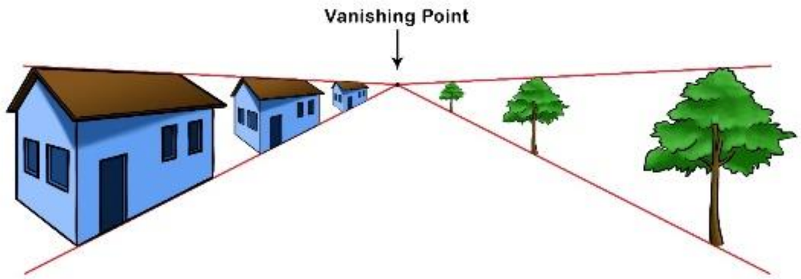



**Figure 1**: Vanishing Point

**Matryoshka doll**

The matryoshka doll is a famous Russian trinket. Encapsulated in the doll is a series of smaller encapsulated dolls. Usually, the height of each doll is 80% of the previous one (Figure 2). If you keep multiplying the size of each doll by .8 as they get smaller and smaller, the size will approach 0 as the number dolls approaches infinity.

**Figure 2:** Matryoshka Dolls [7]

**Pixilation**

Digital photographs are limited by the number of pixels they are comprised of. The size of the pixel approaches zero as the number of pixels approaches infinity. At the theoretical limit, the picture becomes analog. Figure 3 shows the difference between the pixilated image and the analog image of Lincoln. Figure 4 shows the graph as the pixel size approaches zero. Figure 5 shows the resolution as it approaches infinity.

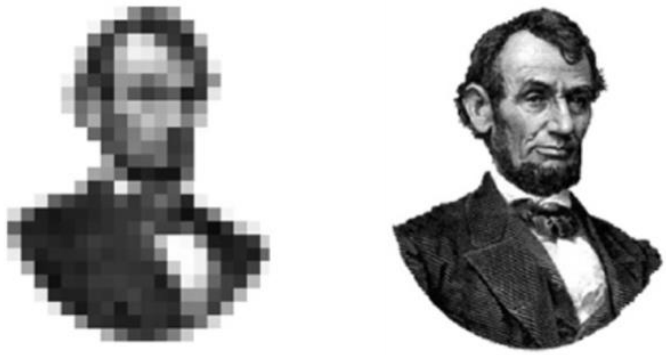


**Figure 3:** Pixelated Lincoln vs Analog Lincoln

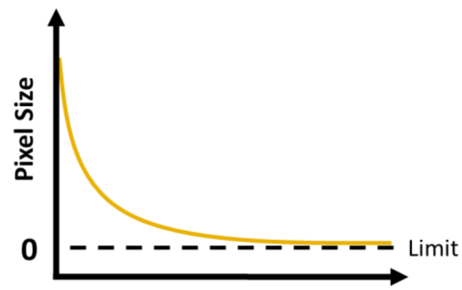



**Figure 4:** Pixel Size Approaching Limit of Zero

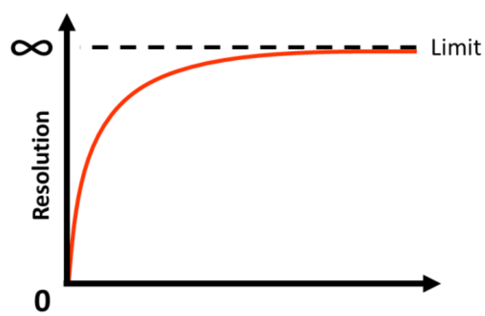



**Figure 5:** Resolution Approaching Infinity

2. **Physics**

**Temperature**

Have you ever wondered how long it takes for a cup of coffee to reach room temperature? Eventually the difference between the coffee temperature and the room temperature (the limit) will become infinitesimally small. For practical purposes, after long time, say 2 hours, it is difficult to distinguish between the temperature of the coffee and the theoretical limit (room temperature). Figure 6 displays the coffee temperature as a function of time.

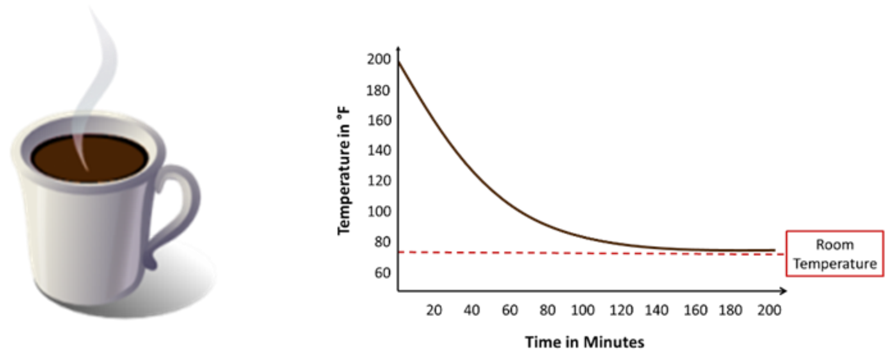



**Figure 6:** Approaching the Limit of Room Temperature

If you wanted to approach the room temperature (the limit) at a slower pace, you may consider using a closed insulating container. This would restrict heat transfer to the environment. The left image of Figure 7 shows the coffee temperature as it approaches its limit. The right image of Figure 7 shows a slower approach due to the insulating container. In both cases, the temperature limit is the same.

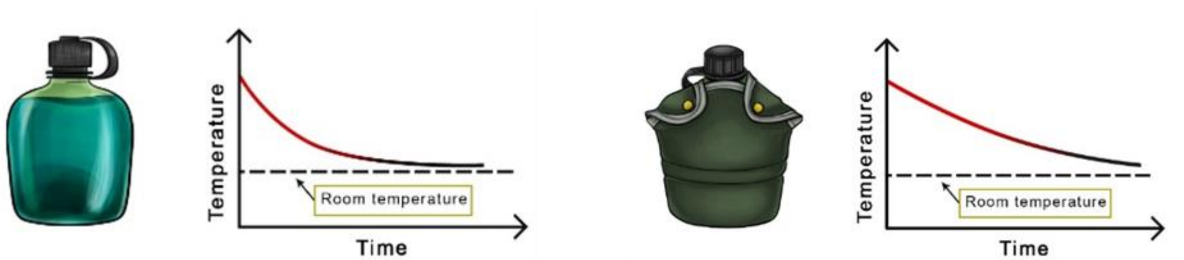



**Figure 7**: Coffee Approaching Limit of Room Temperature by Changing Constant

**Diffusion and Pressure**

Diffusion occurs at an exponential rate. This is when molecules from a region of high concentration move to a region of lower concentration. For example, assume there are two compartments separated by a barrier, one filled with gas molecules and the other with no molecules (vacuum). The left image in Figure 8 shows the state of the molecules before the barrier is removed. The right image in Figure 8 shows pressure equilibrium after the barrier is removed.

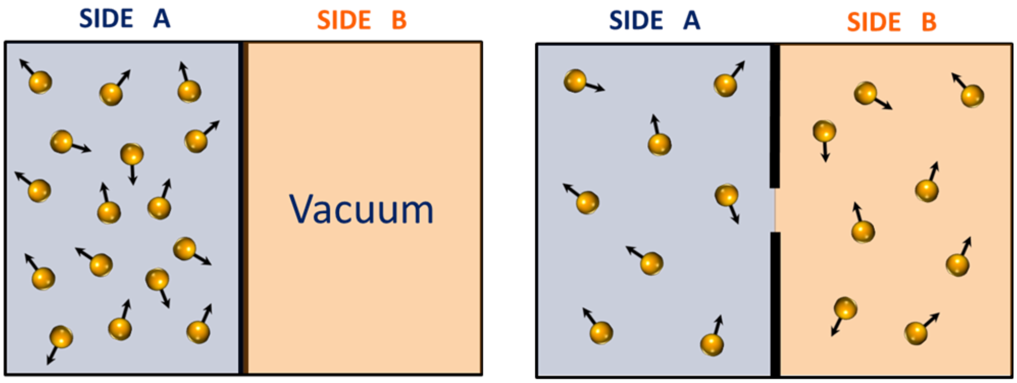



**Figure 8:** Diffusion

Shortly after the barrier between the two chambers is removed, the molecules will reach a state of equilibrium. Side A decreases in pressure, while side B increases in pressure as each chamber approaches the same limit from a different initial pressure. Figure 9 displays the concentrations of molecules in the two chambers as a function of time as they reach an equilibrium point (limit).

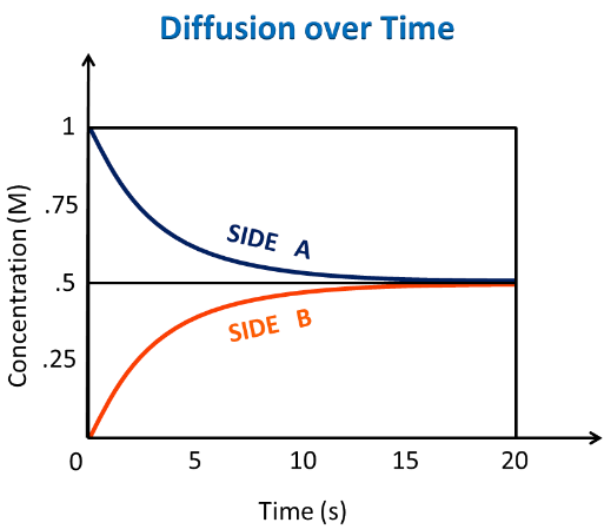



**Figure 9:** Qualitative Concentration of Molecules as Equilibrium is Approached

**Speed of sound and sound barrier**

As an aircraft approaches the speed of sound, the air pressure starts to converge toward the tip of the aircraft. As the speed increases from subsonic to sonic, the sound waves move closer to each other until they are all touching at the same point. This point is known as the sound barrier, which once exceeded creates a sonic boom. Figure 10 displays sound waves or pressure surrounding the aircraft at different speeds.

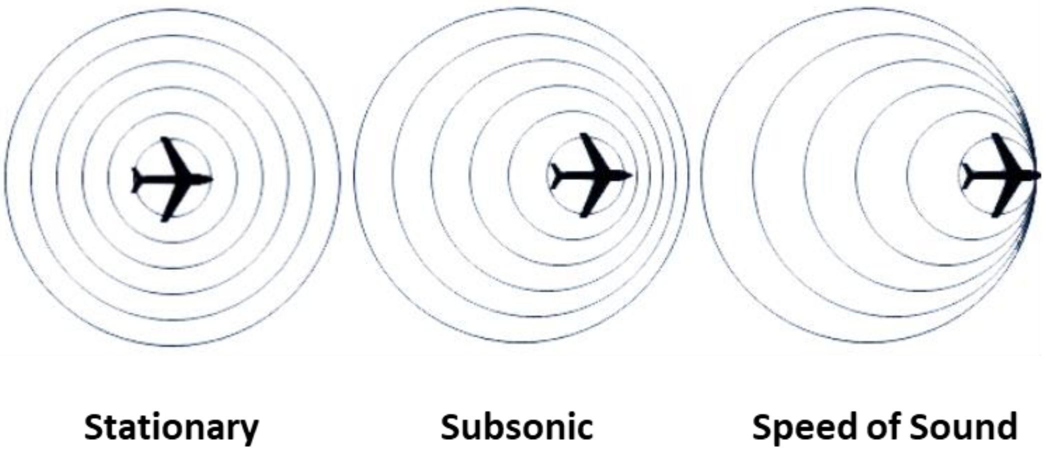



**Figure 10:** Air Pressure Relative to Aircraft Speed

**Fun fact**: Beyond the limit
The image below is a fighter jet after it has exceeded the speed of sound. The convergence of pressure forms a cone as displayed in Figure 11.

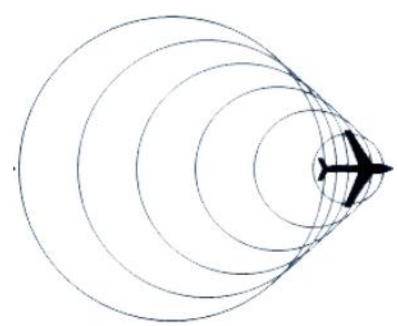


**Figure 11**: Pressure Cone: Beyond the Speed of Sound

Supersonic aircraft structure must be designed to handle the impact at the sound barrier.

## 3. Tech and Engineering

### Car’s acceleration

Two different vehicles accelerate at different rates. If each driver pushes the pedal as far down as possible, each vehicle will achieve maximum acceleration. When the forward force and the drag force (due to relative wind) equal each other, the net force becomes zero and the vehicle’s speed becomes constant. This is where each vehicle reaches its limit of maximum speed (Figure 12).


**Figure 12:** Vehicles with Different Rates of Acceleration

Figure 13 shows the top speeds of the sports car and the truck.

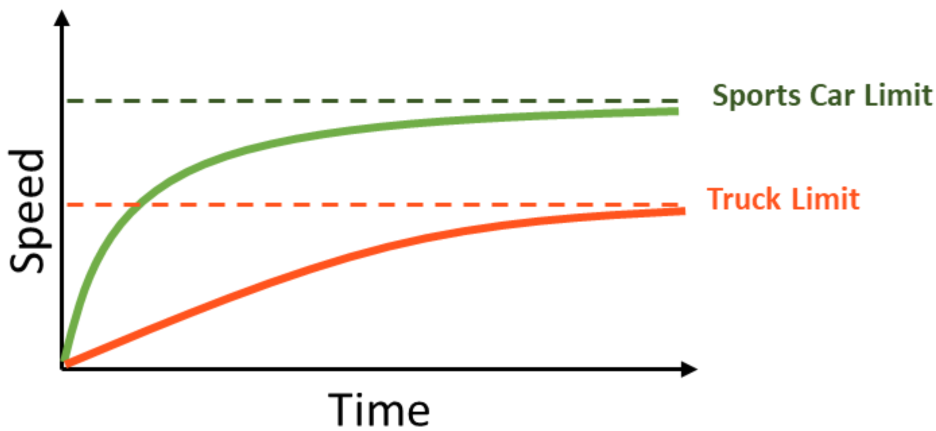



**Figure 13:** Approaching Top Speeds

**The DC Motor**

As we apply maximum constant voltage to a DC motor, it will approach its upper limit of angular velocity, as seen is Figure 14.

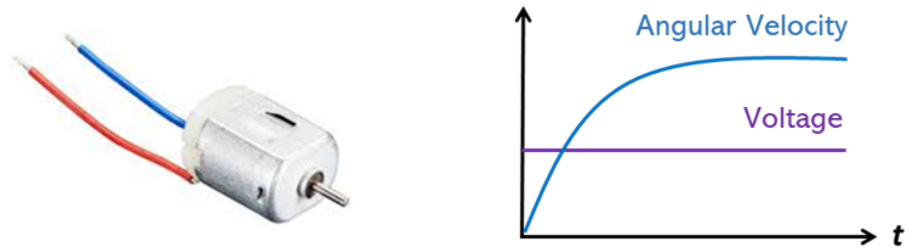



**Figure 14**: Angular Velocity of a DC Motor as a Function of Time

**Cell phone**

The amount of charge that a mobile phone can absorb is limited by an upper level as displayed in Figure 15. Theoretically, it never reaches maximum charge, but it gets very close to its limit.

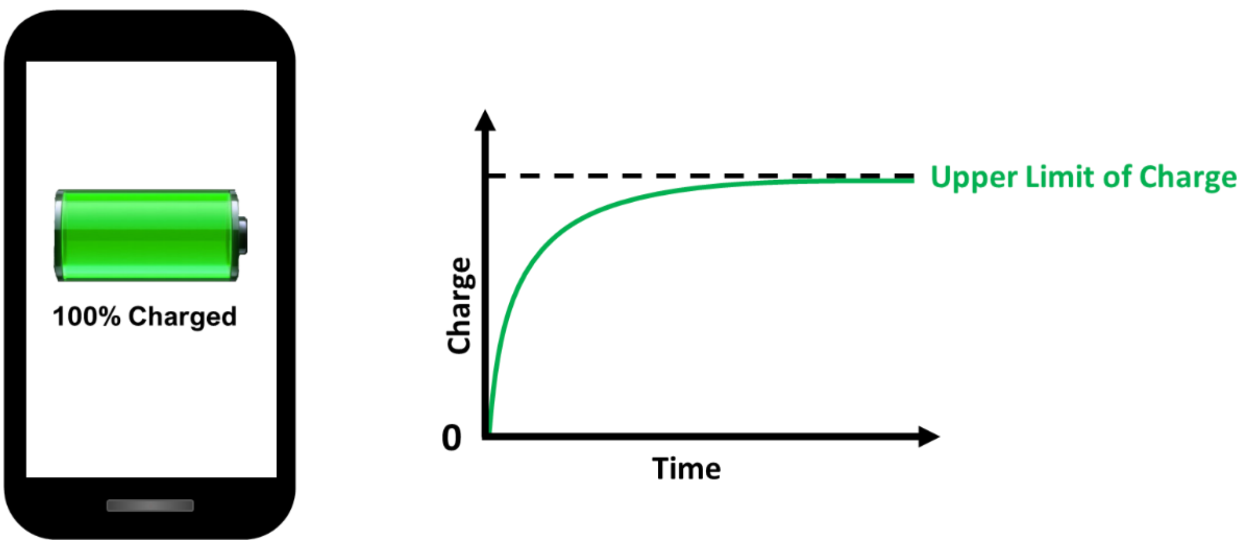



**Figure 15:** Cell Phone Charge as it Approaches Limit of Maximum Charge

## 4. Math

### Two-mirrors

By staring at your own reflecion using two parrallel mirrors, each image will reflect off the other, creating the appearance of an infinite number of images, each of which becomes smaller by the same scale factor relative to the previous image. As the number of reflections approaches infinity, the size of the image approaches the limit of zero.

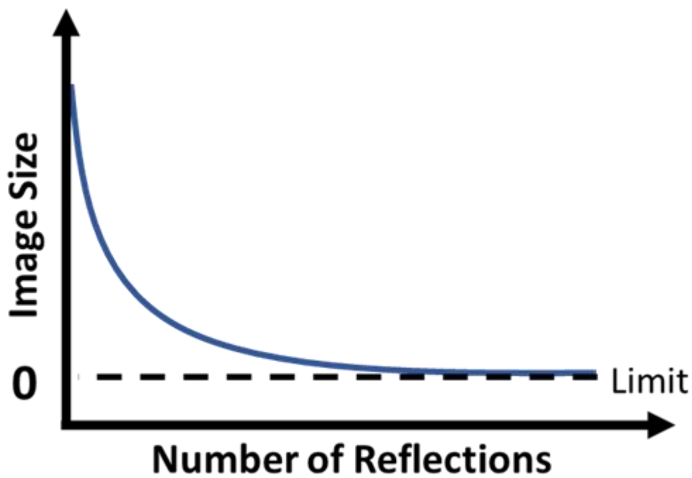



**Figure 16:** Image Size Approaching Limit of Zero as Number of Reflections Increase

### Geometry

This is a classic textbook example. The addition of all areas, each of which is half the size of the previous one (except of course the first one), will eventually approach the limit of 1. $\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\cdots$ is the expression for the total area, which is the sum of a geometric series.

Figure 17 is a graphical illustration of the series.

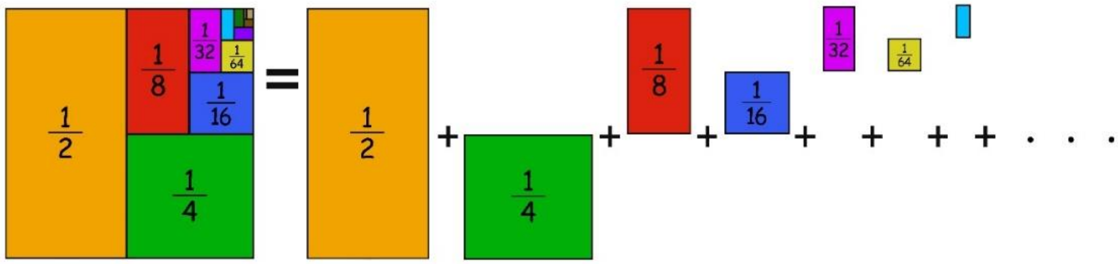



**Figure 17:** Continuously Adding Half of the Previous Area

**Fractals**

A fractal is a geometric shape with self-similar branches. These branches form a never ending, repeating pattern. The resulting perimeter has no limit as the branches repeat to infinity. However, the area of the pattern will approach a finite limit. Figure 18 displays the progression of two fractals with a triangle as its base.

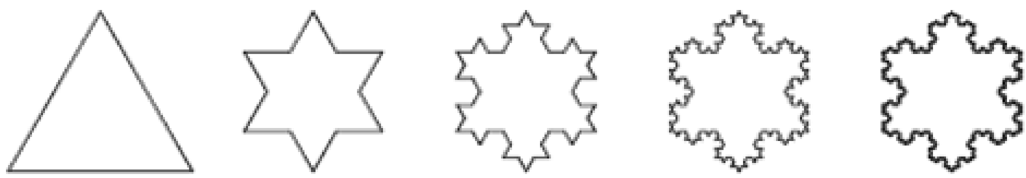


**Figure 18:** Fractals

**The Golden Ratio Phi and Fibonacci Series**

The Fibonacci sequence describes a pattern where each number is the sum of the two previous numbers starting with “0” and “1.” If you add the “0” and “1”, you get “1”. Then add “1” and “1” to get “2.” The sequence becomes 0,1,1,2,3,5,8,13,21,34,55,89,144,…
The limit of the ratio of two consecutive numbers in the Fibonacci series approaches the golden ratio ( $\frac{1+\sqrt{5}}{2}$ ) known as phi (the Greek Alphabet letter $\varphi$) which is approximately 1.618.

**Rabbit Population and the Golden Ratio**

To better visualize the golden ratio, we use an example involving immortal rabbits.

All rabbit pairs are not fertile during their first month of life. They give birth to one new male/female pair at the end of the second month and every month thereafter (…forever).

Refer to Figure 19 below.

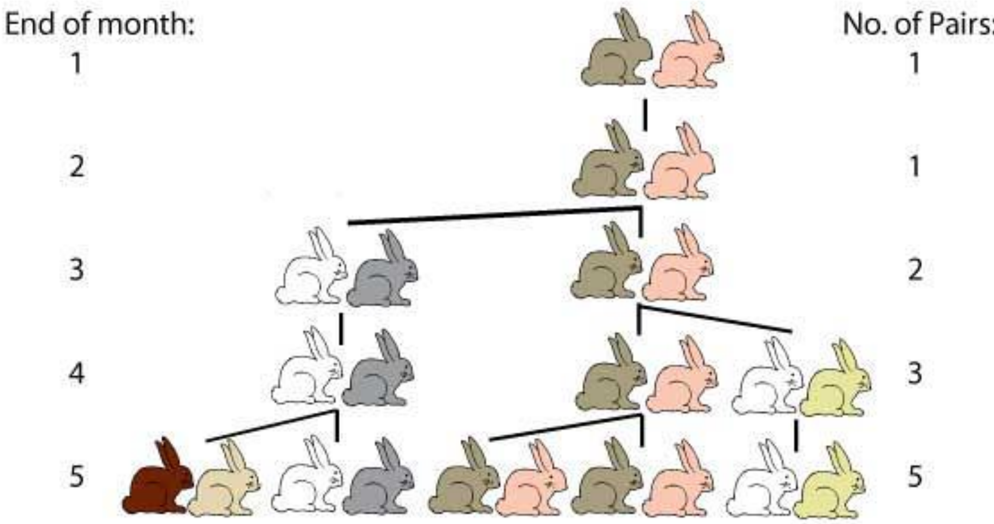



**Figure 19**: Fibonacci Rabbits after Each Month

As each month passes, a pattern immerges. Adding the number of pairs from the two previous months provides the value of rabbit pairs in the current month, as seen in Figure 20.

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # of Pairs | 1 | 1 | 2 | 3 | 5 | 8 | 13 | 21 | 34 | 55 | 89 | 144 |

**Figure 20:** Number of Pairs Each Month

By dividing the total rabbit population after each month by the previous total, the ratio (as the sequence goes to infinity) reaches a limit. This is also the Golden Ratio $\varphi$.

## Ratio of Rabbit Population

| Rabbits | φ ratio |
|---|---|
| 1 | ***** |
| 1 | 1.0000 |
| 2 | 2.0000 |
| 3 | 1.5000 |
| 5 | 1.6667 |
| 8 | 1.6000 |
| 13 | 1.6250 |
| 21 | 1.6154 |
| 34 | 1.6191 |
| 55 | 1.6176 |
| 89 | 1.6182 |
| 144 | 1.6179 |

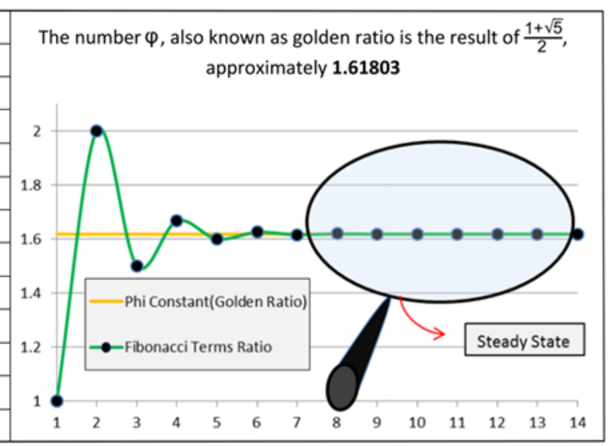



**Figure 21:** Rabbit Population Ratio as it Coincides with Golden Ratio

**The number e**

You have one dollar and want to start investing it, so you meet with a financial adviser. He or she is willing to give you a 100% return on the $1 you invest after one year, for a total of $1 + $1(simple interest) = $2. The next advisor is willing to give you a better deal. The interest will compound twice in one year. As you consult with more advisors, they keep offering a larger number of times (n) the interest is compounded per year. The larger the number (n), the higher the return you receive after one year. Eventually when n approaches infinity (i.e., compounded interest every infinitesimally small-time interval) the limit will become "$e" i.e., ~$2.718" … by far better than the $2 with a simple interest. In mathematical notation it looks like:

$$\lim_{n\to\infty}\left(1+\frac{1}{n}\right)^{n} = e$$

For different values of n you get:

$$\left(1+\tfrac{1}{1}\right)^{1} = 2$$
$$\left(1+\tfrac{1}{2}\right)^{2} = 2.25$$
$$\left(1+\tfrac{1}{3}\right)^{3} = 2.37037\ldots$$
$$\left(1+\tfrac{1}{10}\right)^{10} = 2.593743\ldots$$
$$\left(1+\tfrac{1}{n}\right)^{n} = \ldots$$

**Figure 22:** Value of Financial Return Reaching Limit of e as Number of n Increases

An alternative way of looking at it is shown in figure 23.

$$\left(1+\tfrac{1}{1}\right)^{1} = \left(100\% + \tfrac{100\%}{1}\right)^{1} = 200\%$$
$$\left(1+\tfrac{1}{2}\right)^{2} = \left(100\% + \tfrac{100\%}{2}\right)^{2} = 225\%$$
$$\left(1+\tfrac{1}{3}\right)^{3} = \left(100\% + \tfrac{100\%}{3}\right)^{3} \cong 237\%$$
$$\left(1+\tfrac{1}{10}\right)^{10} = \left(100\% + \tfrac{100\%}{10}\right)^{10} \cong 259\%$$
$$\left(1+\tfrac{1}{n}\right)^{n} = \left(100\% + \tfrac{100\%}{n}\right)^{n}$$

$$\lim_{n\to\infty}\left(1+\tfrac{1}{n}\right)^{n} = \lim_{n\to\infty}\left(100\% + \tfrac{100\%}{n}\right)^{n} = 100\%\,e$$

**Figure 23:** Return on Investment Illustrated in Percentage

**Slope/tangent**

The more you magnify the slope of a curve at a specific point, the closer it appears as a straight line, also known as the tangent. At the limit the curve becomes the tangent line.

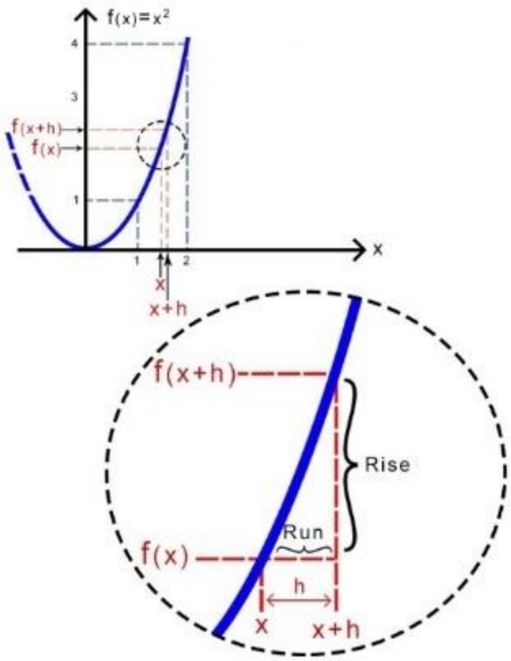



**Figure 24:** Zooming in on Slope of Curve

**Integration**

You can approximate the area under the function by adding all the areas of the small rectangles below the graph, or by adding all the areas of the larger rectangles above as displayed in Figure 25. As you reduce the width of the rectangles to become infinitely small, the total area of the upper rectangles will approach the total area of the lower rectangles, and at the limit this becomes exactly the area under the graph.

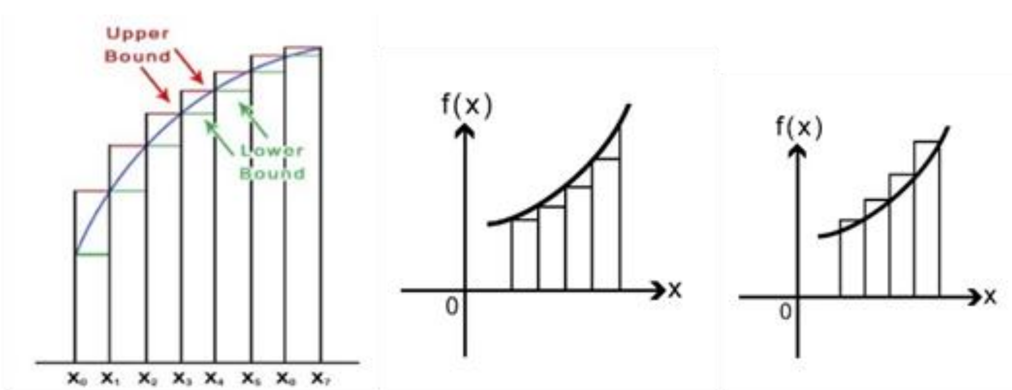



**Figure 25:** Integration by Adding Sum of Rectangles

**L’Hopital Rule**

Try to divide sin(x)/x as x approaches zero. This results in zero divided by zero which is unsolvable. L’Hopital states that to find the limit, you take the limit of the derivative of the numerator divided by the limit of the derivative of the denominator and apply x =0. In our case, the limit of sin(x)/x as x approaches zero becomes have cos(x) /1 when x =0 which becomes 1.

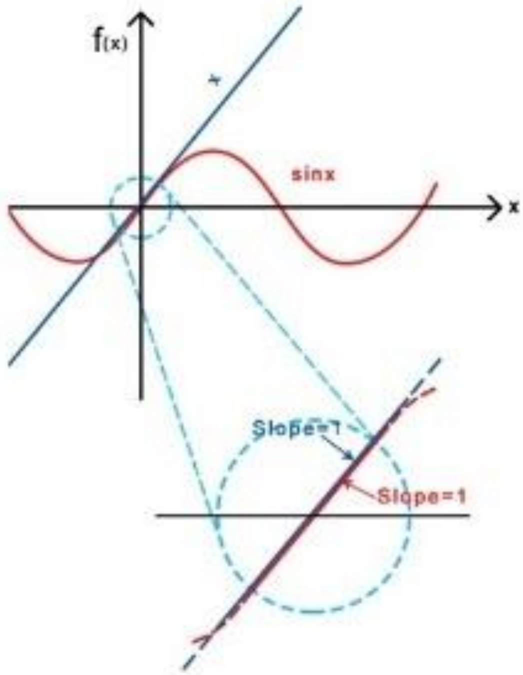



**Figure 26:** Visualizing L'Hopital Rule

## 5. Brain Teasers

**Pizza**

In front of you there are two different ring pizzas (Figure 27). You *do not know* the size of the pizzas, but you *do know* that they share a common tangent to the inner circle, which is 20cm. You also know that both pizzas have the *same area.*

The question is, what is the area of each pizza?

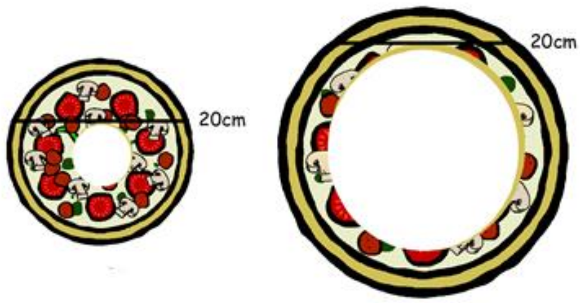



**Figure 27**: Two Pizzas Missing Area

*Solution:* Since the area of the pizza depends only on the length of the inner tangent: reduce the diameter of the pizza to its smallest possibe size to make a new pizza (without a hole) with a diameter of 20cm (the length of the tangent of the inner circle). It has the same area as the other two pizzas.

The area of each of the other two pizzas is the same as the area ("A") of the new pizza, i.e.,

$$A = \pi\left(\frac{(20cm)^2}{4}\right) = 100\pi\, cm^2$$

**Infinite Circles**

Inside a triangle, there are an infinite number of circles that become smaller as the triangle converges at the top (Figure 28). How do you measure the sum of all the circles' perimeters? *Solution:*

The sum of all the perimenters is the sum of each of the circle's diameter multiplied by $\pi$. Since you know the sum of all the diameters which is the height of the triangle, all you have to do to get the solution is to multiply the height of the triangle by $\pi$.

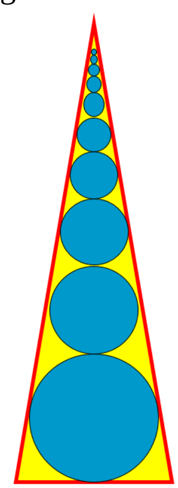


**Figure 28:** Infinite Circles Contained in a Finite Triangle

**Super Fly**

Two trains are 120 miles apart, and moving towards each other at 60 and 140mph. Flying between the trains is a “super fly”. It flies back and forth between the trains at a speed of 360mph until both trains collide. How do you determine the distance the fly has traveled?

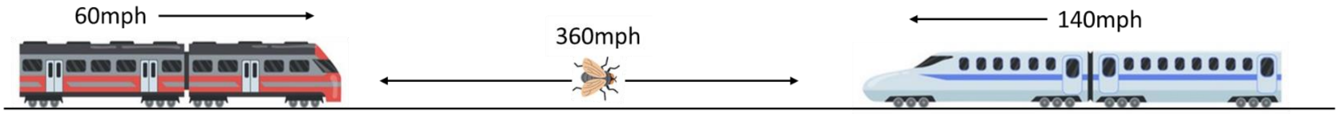



**Figure 29:** Superfly Flying Back and Forth Between Two Colliding Trains

*Solution:* If the trains are 120 miles apart heading towards each other at a relative speed of 200mph (60+140=200), you determine the time until collision by dividing the distance by the relative speed, i.e., 120miles/200mph = 0.6 hours. This is also the amount of time the fly spent traveling. So now that you have the travel time, multiply the time the fly flown by its speed to get: 360mph x 0.6 hours= 216 miles.

## III. Conclusion

The examples in this paper were chosen to introduce the concept of limit in visual and intuitive ways. These examples are designed to simplify explanations of the concept, and to relate it to everyday life experiences. The explanations intentionally do not focus on numerical solutions or heavy mathematics to avoid intimidating students. The end goal is to inspire the “aha moment” prior to transitioning to a more scientific or mathematical explanation. The paper does not attempt to replace current teachings, lesson plans or textbooks, but rather provide supplementary material.

We hope that those who teach the topic of limit will use some of these examples as a supplement to their teaching, and that students find this resource helpful in comprehending a concept that is widely regarded as difficult. This work has not yet been tested in a classroom setting, but similar work on other topics has been received positively by students and instructors.

## IV. Acknowledgements

The author thanks the reviewers for several important comments that led to several specific improvements, and to Mr. Martinson who carefully reviewed the paper and provided very useful suggestions. Special thanks to Dr. Adelmann, the Calculus class instructor who allowed to remotely present the material to students, and to assess the presentation using an anonymous questionnaire. Special thanks to Mr. Juan Yepes for his help in visualizing the assessment results.

## V. References


[1] T. Goldfinch, A. L. Carew, and T.J. McCarthy, "Improving Learning in Engineering Mechanics: The Significance of Understanding Causes of Poor Performance," in *Proceedings of the 2008 AAEE Conference*, 2008.

[2] S. Baker and L. Talley, "The Relationship of Visualization Skills to Achievement in Freshman Chemistry," in *Journal of Chemistry Education*, 1972.

[3] J. Velazquez-Iturbide, I. Hernan-Losada, and M. Paredes-Velasco, "Evaluating the Effect of Program Visualization on Student Motivation," in *IEEE Transactions on Education*, 2017.

[4] D. Raviv, "Have you seen an integral? Visual, intuitive, and relevant explanations of basic engineering-related mathematical concepts," in *Proceeding of the ASEE National Conference*, Salt Lake City, UT, June 2018.

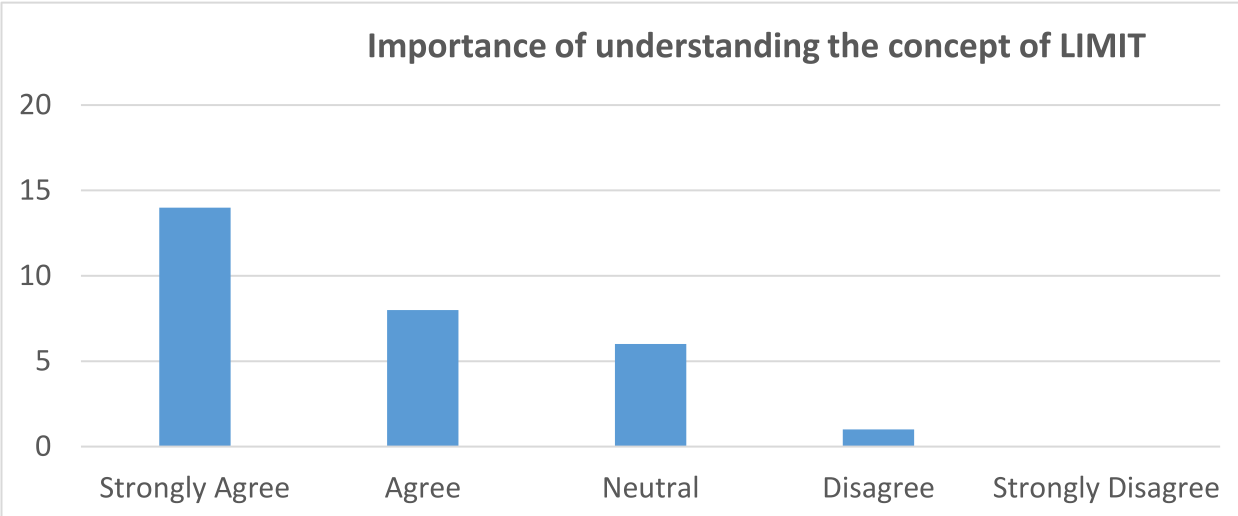
[5] R. Booth and M. Thomas, "Visualization in Mathematics Learning: Arithmetic Problem-Solving and Student Difficulties," in *Journal of Mathematical Behavior*, 1999.

[6] S. Jin, "Using Visualization to Motivate Student Participation in Collaborative Online Learning Environments," in *Educational Technology and Society*, 2017.

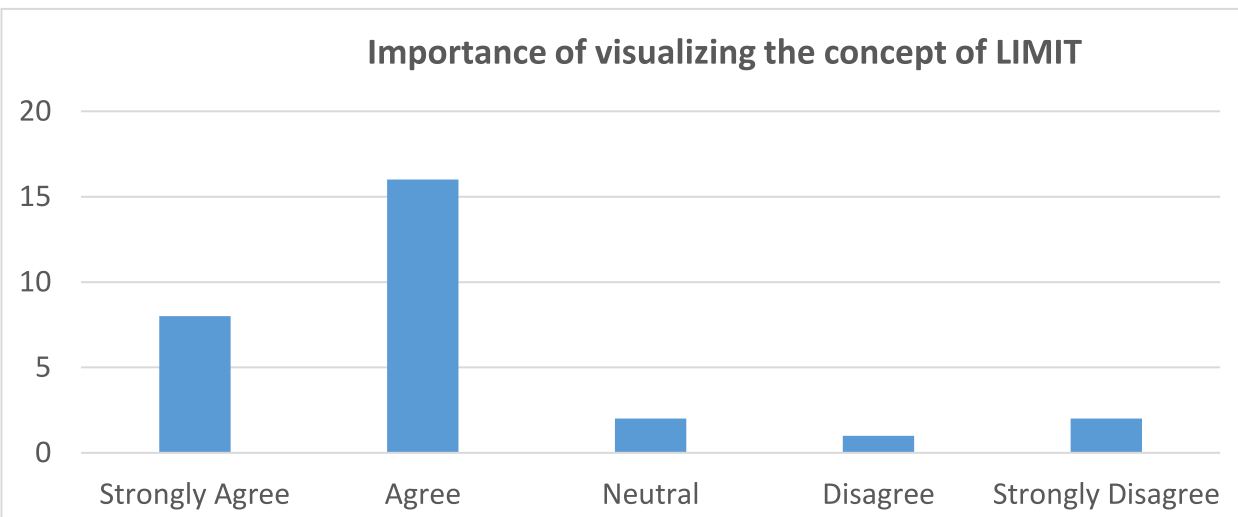
[7] https://www.dookinternational.com/blog/russian-doll-centuries-old-tradition-and-masterart/

**Appendix: Assessment**

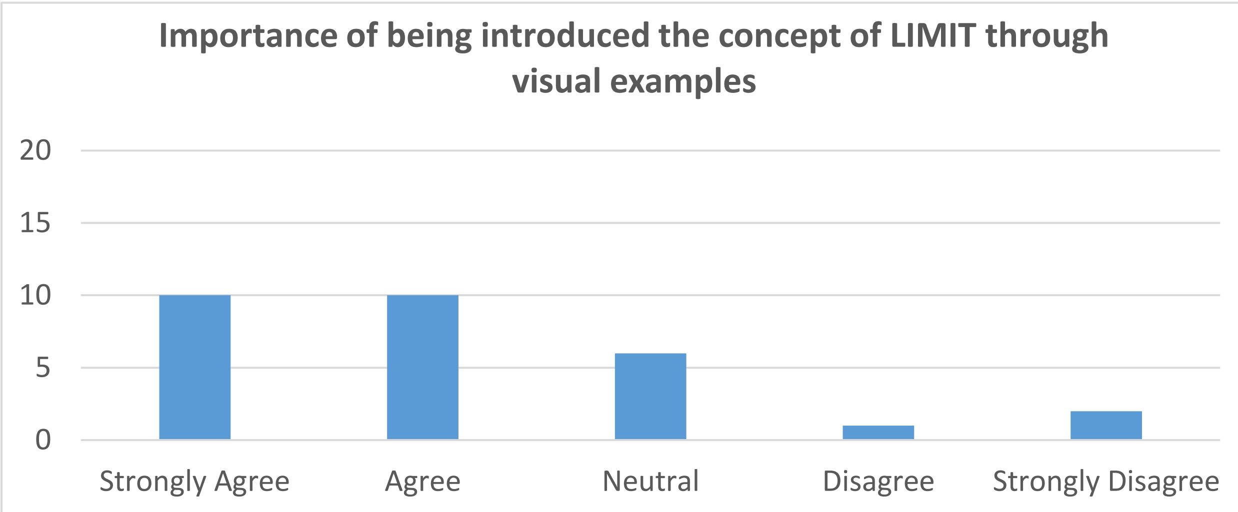
**Q1:**



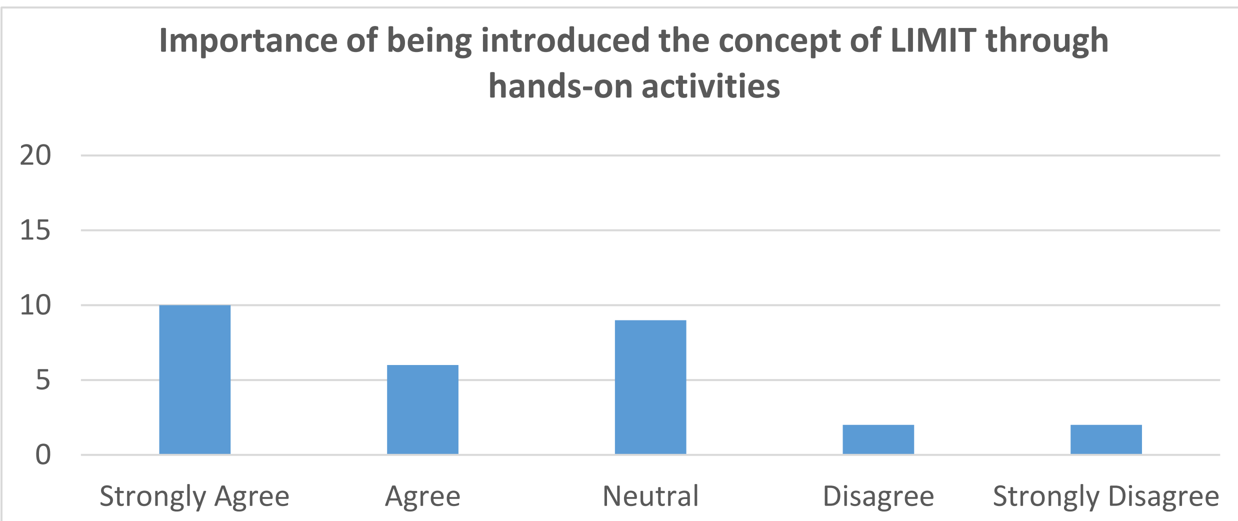

**Q2:**



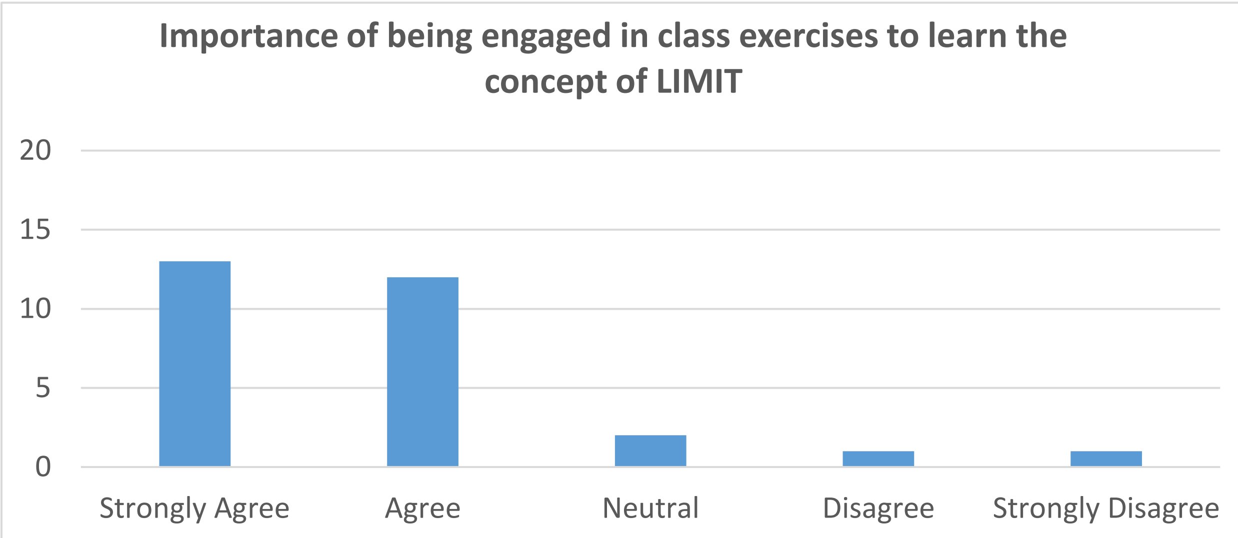
**Q3:**


Importance of being introduced the concept of LIMIT through visual examples
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

**Q4:**

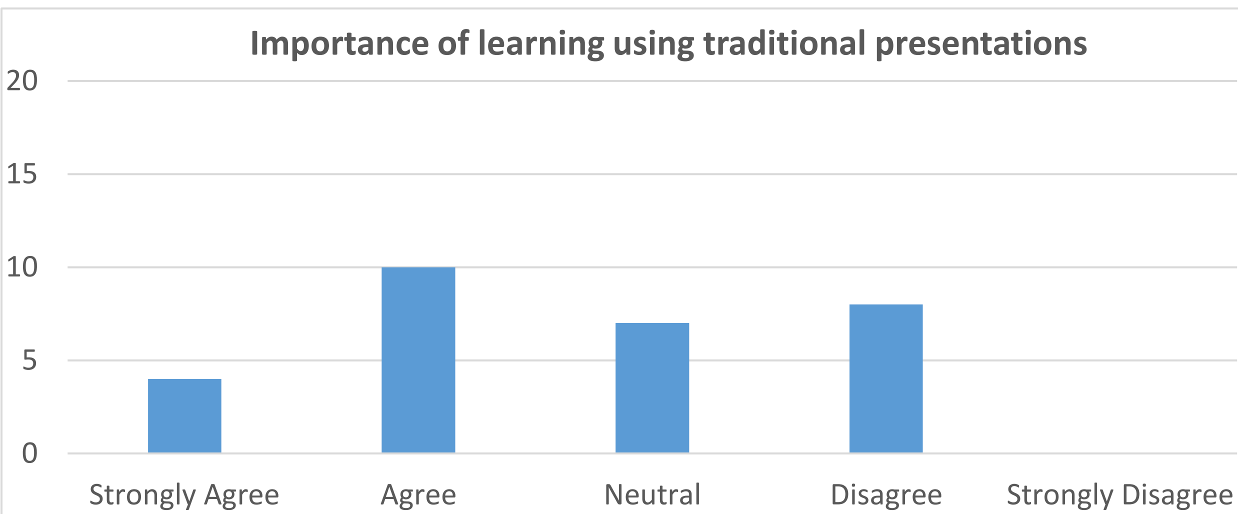

Importance of being introduced the concept of LIMIT through hands-on activities
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

**Q5:**



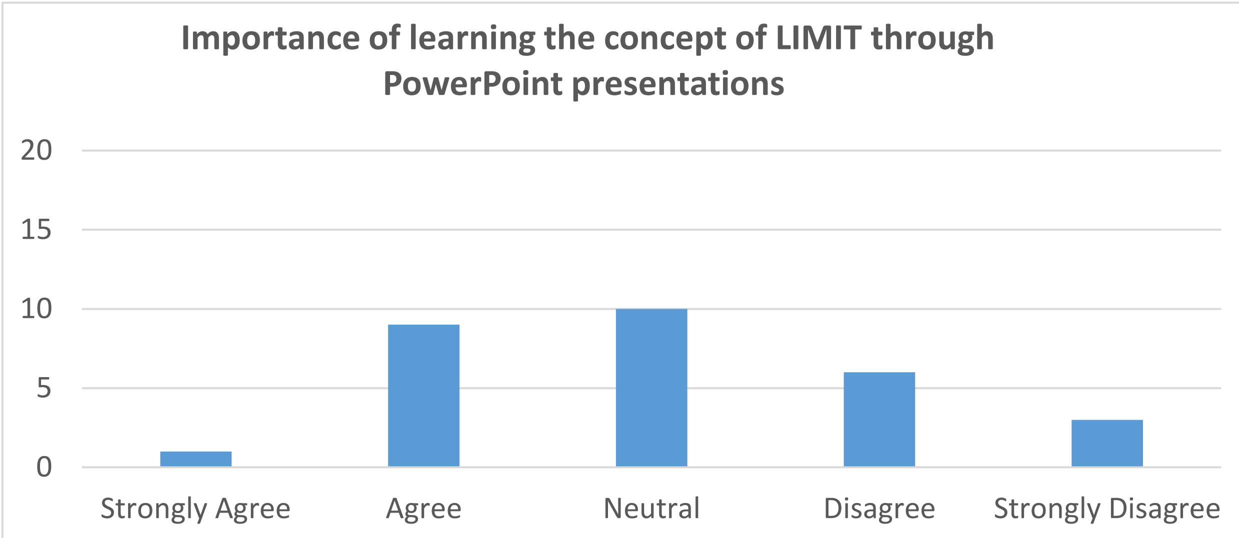
Importance of being engaged in class exercises to learn the concept of LIMIT
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree


**Q6:**

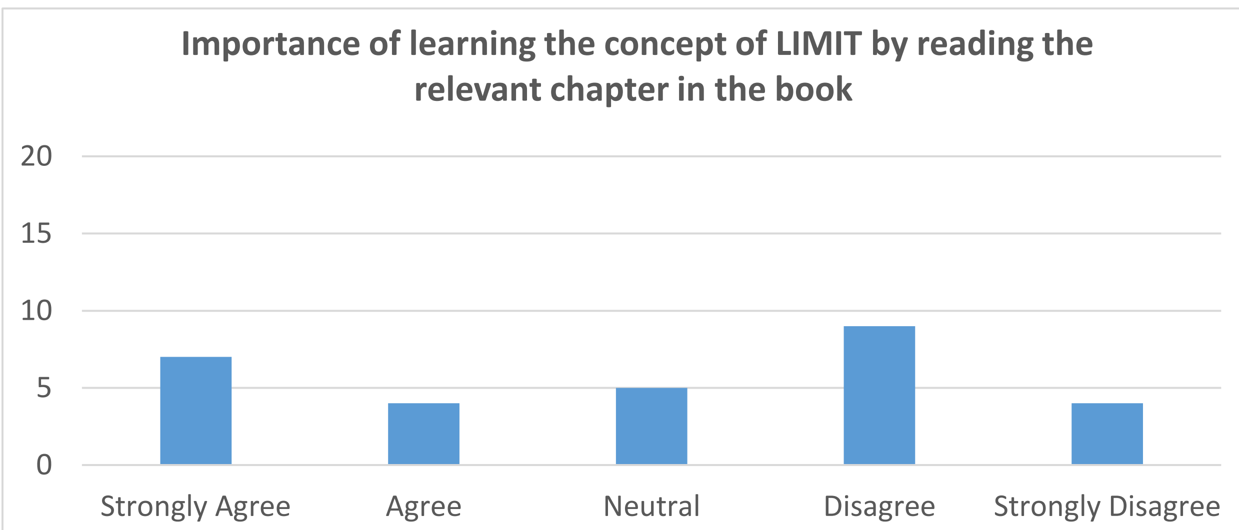


Importance of learning using traditional presentations
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

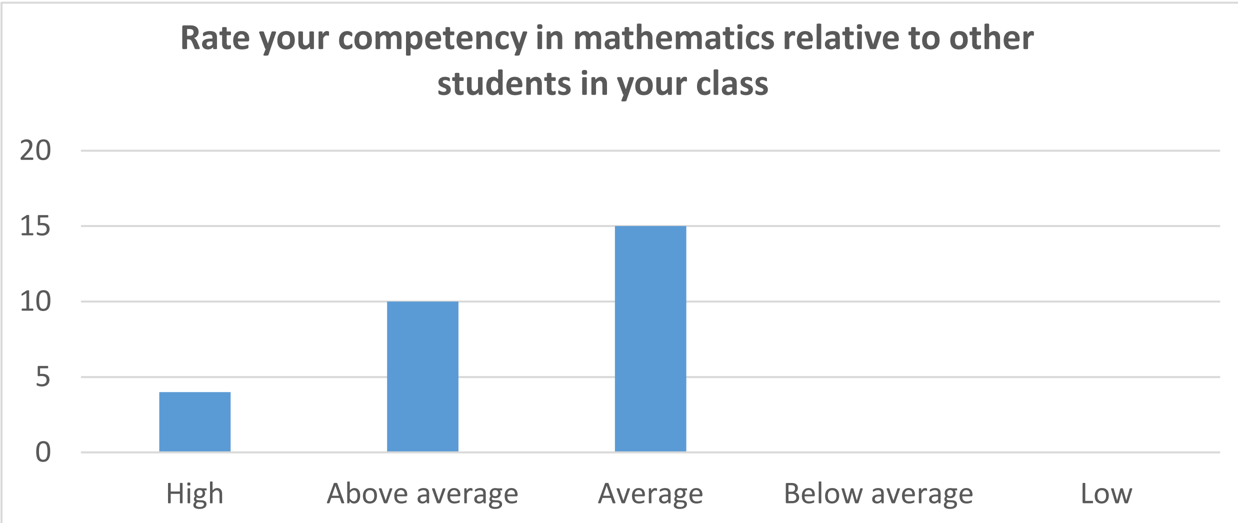
**Q7:**


Importance of learning the concept of LIMIT through PowerPoint presentations
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

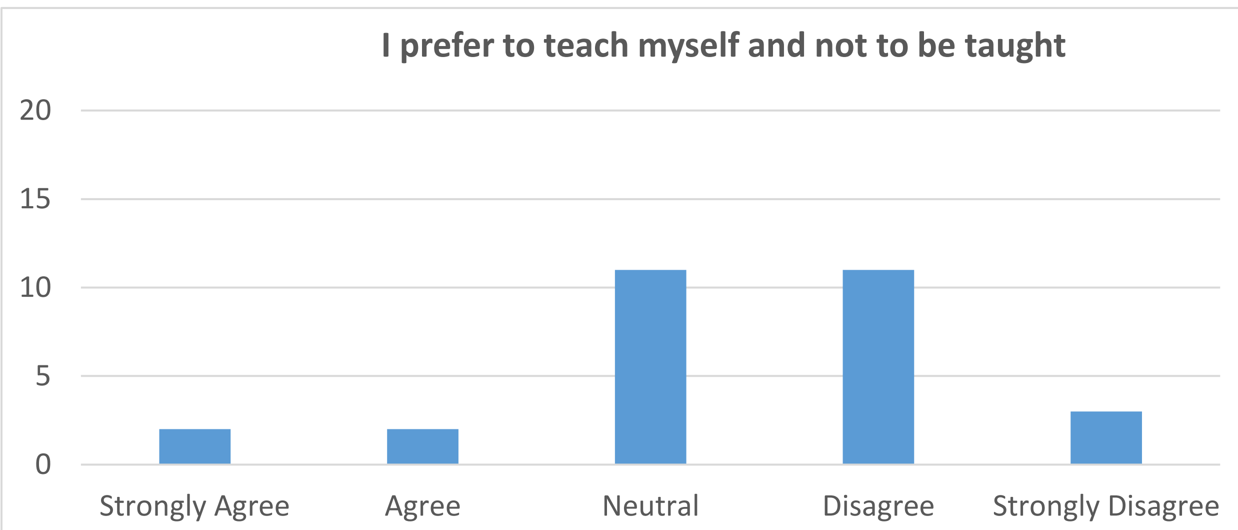
**Q8:**


Importance of learning the concept of LIMIT by reading the relevant chapter in the book
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree

**Q9:**


Rate your competency in mathematics relative to other students in your class
20
15
10
5
0
High
Above average
Average
Below average
Low

**Q10:**


I prefer to teach myself and not to be taught
20
15
10
5
0
Strongly Agree
Agree
Neutral
Disagree
Strongly Disagree