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Ethnomathematics: The exploration of fractal geometry in Tian Ti Pagoda using the Lindenmayer system

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***Abstract*:**
This study explores the concept of fractal geometry found in the Tian Ti Pagoda. Fractal geometry is a branch of mathematics describing the properties and shapes of various fractals. A qualitative method with an ethnographic approach is used in this study. Observation, field notes, interviews, documentation, and literature study obtained research data. The observation results were processed computationally using the Lindenmayer system method via the L-Studio application to view fractal shapes. The results show that the concept of fractal geometry is contained in the ornaments on the Tian Ti Pagoda. The length and angles of each part of the ornament influence the fractal shape of the Tian Ti Pagoda ornament. In addition, the length and angle modifications resulted in several variations of the Tian Ti Pagoda fractal. The findings from this study can be used as an alternative medium for learning mathematics lectures, especially in applied mathematics, dynamical systems, and computational geometry.

Keywords: Ethnomathematics, Fractal Geometry, Lindenmayer System, Tian Ti Pagoda

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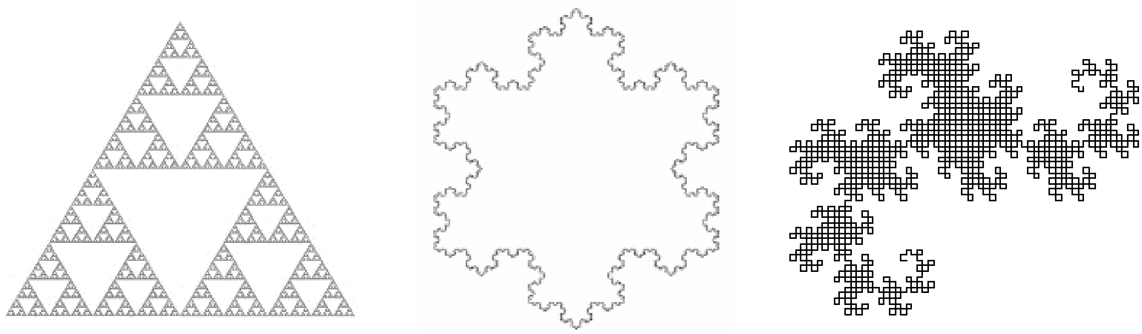
Introduction

Academic math is math that is learned in school. Meanwhile, mathematics learned in specific cultural groups is called ethnomathematics. Ethnomathematics was first introduced in 1977 by a mathematician from Brazil, Ubiratan D'Ambrosio (d'Ambrosio, 2001; Orey & Rosa, 2008). Ethnomathematics combines culture, mathematics, and education obtained through research on a particular cultural group to understand, apply, and apply mathematical concepts. Studying ethnomathematics is essential to see the use of mathematical concepts and explore mathematics in people's cultures (Gerdes, 2017; Orey & Rosa, 2008). One ethnomathematics object was seen in the ornaments that decorate traditional houses and cultural heritage buildings.

Field studies show a strong interaction between mathematics and community culture, especially in traditional house ornaments (Alghar et al., 2022; Ditasona, 2018;

Sulaiman & Nasir, 2020). They found mathematical concepts in them, including the idea of geometry transformation, symmetry patterns, and flat shapes in Minangkabau Gadang house ornaments (Fitriza, 2018), the concept of geometry transformation consisting of translation, rotation, and dilation in Gorga ornaments (Ditasona, 2018), and the idea of arithmetic sequence in Gadang house Singok Gonjong ornaments (Alghar et al., 2022). However, this research is still limited to exploring basic geometric concepts, such as points, lines, angles, congruence, flat shapes, and geometric transformations. So, the findings are still limited to Euclid geometry (Lee & Tiong, 2013; Sulaiman & Firmasari, 2020). Ethnomathematics studies at an advanced level are needed to see more complicated geometric concepts, one of which is the concept of fractal geometry.

Fractal geometry is a branch of mathematics explaining the properties and shapes of various fractals. Fractals do not have a standard form, so they do not include objects defined in Euclid geometry (Romadiastri, 2017; Sulaiman & Firmasari, 2020). Furthermore, fractals have infinite details and resemble themselves or self-similarity at every level (Prusinkiewicz & Lindenmayer, 2012; Yildiz & Baltaci, 2017). Some fractal shapes include the Sierpinski triangle, Mandelbrot set, Koch snowflake curve, and dragon curve (Kushwaha & Kumar, 2013; Romadiastri, 2017). In addition, fractal shapes can also be found in nature, such as waves, mountains, clouds, plant branching, lightning, and others. Visually, fractals have high artistic and aesthetic value (Juhari & Alghar, 2021; Prusinkiewicz & Lindenmayer, 2012).



Source: Prusinkiewicz & Lindenmayer, 2012 and Romadiastri, 2017

Picture 1. Some examples of fractal visualization: (a) Sierpinski triangle; (b) Koch snowflake curve; (c) Dragon curve.

On the other hand, learning about fractal geometry is still difficult for students to understand. Yi (2004) explained that students tend only to follow the procedures in constructing fractal shapes without understanding their mathematical ideas. Students also experience difficulties in developing other fractal conditions (Abu-Elwan, 2014; Bahar & Maker, 2020). In addition, the fractal forms shown are still limited to natural and mathematically structured fractals, even though there are still different fractal geometric shapes whose existence can be explored, such as in traditional house decorations or ornaments.

One of the ornaments with a fractal shape is the ornament on the Tian Ti Pagoda. Tian Ti Pagoda is a replica of the Pagoda in Beijing, namely the Temple of Heaven Pagoda. Tian Ti Pagoda is one of the places of worship in the Kenjeran Panorama Ria Family or Kenpark area. As a replica pagoda of the Temple of Heaven Pagoda, Tian Ti Pagoda is enveloped in various Chinese-style things, from architecture to ornaments.

Architecturally, Tian Ti Pagoda has a diameter of 60 meters and a height of 58 meters. In terms of ornamentation, Tian Ti Pagoda has many cultural patterns originating from China (Yuniana, 2016).

Picture 2. Tian Ti Pagoda

Some Chinese culture is found in Tian Ti Pagoda, such as the predominantly red color, regular geometric shapes, and patterns that have aesthetic value (Yuniana, 2016). Chinese ornaments generally have an infinite balance of straight, oblique, and curved, representing the close relationship between geometry and mathematics (Lee & Tiong, 2013; Wen, 2011; Xu et al., 2020). Furthermore, regularity is a crucial feature of Chinese ornamentation. The absolute and regular arrangement of geometry is made freely in the regularity that characterizes it (Dye, 2012; Wen, 2011). The Chinese ornaments on Tian Tii Pagoda are shown in Picture 3.

Picture 3. Chinese ornaments on Tian Ti Pagoda

Yuniana (2016) has studied the study of ornaments at Tian Ti Pagoda within the scope of culture and anthropology. However, mathematical breakdowns of Tian Ti Pagoda ornaments are still minimal, so researchers feel the need to study these ornaments mathematically. Furthermore, the ornaments on Tian Ti Pagoda have repetitive and irregular shapes, so they are included in non-Euclid geometry. In this case, the authors will explore the Tian Ti Pagoda ornaments in fractal geometry.

The fickle nature of fractals makes it impossible to formulate using Euclidean geometry methods (Abu-Elwan, 2014; Juniati & Budayasa, 2017). Therefore, a unique technique is needed to see the mathematical form of fractals, one of which is the Lindenmayer system or L-system. L-system is a technique developed by Astrid Lindenmayer that uses geometric transformations as its basis, which is computerized to produce a shape or visual object (Bernard & McQuillan, 2021; Prusinkiewicz & Lindenmayer, 2012). Computationally, the Lindenmayer system rewrites strings with specific iterative and recursive rules. That is, the rules that are made are repetitive and return to the initial function. (Juhari & Alghar, 2021; Juniati & Budayasa, 2017).

Formally, an L-system is described as a sequential tuple $G = (V, \omega, P)$. V as a collection of alphabets or a finite set of symbols, ω as axioms strung on V, and P as a set of productions on a finite set or rewrite rules. A deterministic context-free L-system or D0L-system has a rule $A \to x$, where $A \in V$ is called the initiator, and x is a string in V called the generator of A. The generator x maps exactly one production rule to every A member of V as the initiator (Bernard & McQuillan, 2021; Prusinkiewicz & Lindenmayer, 2012).

Suppose the L-system is given a string $\omega_i = A_1 ... A_m$ for each $A_i \in V, 1 \leq \ i \leq m$, then the symbol $\to$ is defined as the mapping $A_1 ... A_m \to x_1 ... x_m$, where $A_i \to x_i$ is in P for each $i, 1 \leq i \leq m$. When this process is repeated $n - 1$ times, the process starts with the axiom $(\omega = \omega_1 \to \omega_2 \to \cdots \to \omega_n)$. The sequence $\omega_1, \omega_2, ... \omega_n$ is called the n-sequence length. Then each initiator and generator is given certain symbols as instructions for positioning and drawing in 2D or 3D space (Bernard & McQuillan, 2021).

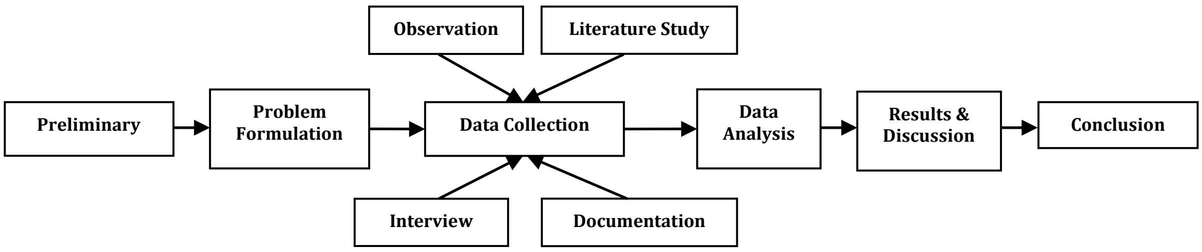
For example, the F symbol signifies a line advancing along one step and is presented visually, while the f symbol represents moving one step but is not presented visually. The $+$ or $-$ symbol signifies rotating counterclockwise or clockwise for 2D space. In 3D space, the $\&$ or $\wedge$ symbol controls up or down rotation. The $/$ or $\backslash$ symbol indicates left or right rotation in 3D space (Juhari & Alghar, 2021; Prusinkiewicz & Lindenmayer, 2012).

The geometric shapes found in the Tian Ti Pagoda ornaments seem rather complicated when studied in Euclid geometry. In addition, its visually repetitive form allows it to be checked with fractal geometry. So, this study aims to explore fractal geometry in Tian Ti Pagoda ornaments using the Lindenmayer system method.

Picture 4. Ornamental parts to be studied on Tian Ti Pagoda

Research Methods

This research method was conducted qualitatively with an ethnographic approach. The research stages were carried out with (1) The preliminary stage, namely determining the topic, object, and place of research. At this stage, the researcher selected ethnomathematics as the research topic, the Tian Ti Pagoda as the research location, and the Chinese ornaments on the Tian Ti Pagoda as the research object; (2) The stage of formulating research problems; (3) Researchers carried out the data collection stage in several steps. The observation begins by determining which part of the ornament is considered to have a fractal shape. The observation is continued by collecting data in the form of the length and angle of the ornament. Data from the measurement results were recorded in research notes for later analysis. The researcher took the data in images as a comparison with the analysis results. Researchers with Mrs. Jing-Jing conducted interviews as the manager of Tian Ti Pagoda. Researchers used interview guidelines that had been validated. A literature study was conducted through books, journals, and documents related to Chinese ornaments and fractal geometry; (4) The data analysis stage. Data were obtained from observation results, field notes, interviews, and documentation. Data validity was obtained using methodological triangulation. That is, researchers analyzed data by comparing visualization results, interview results, observation results, and the results of literature studies. Data analysis is done by reducing and processing computationally with the Lindenmayer system in the L-Studio application to see the fractal shape. Then the data is presented descriptively and visually to be concluded.

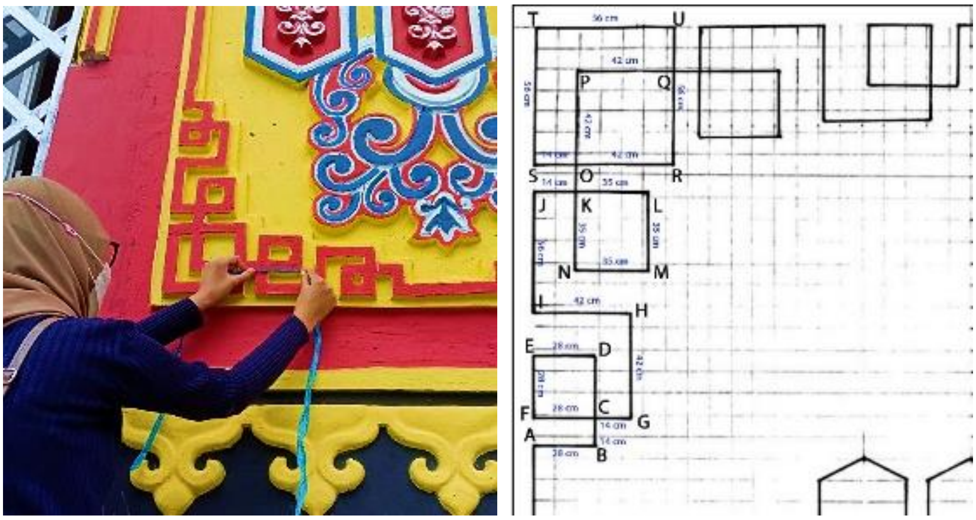


Picture 5. Research Stages

Results and Discussions

Observation Results

This section will explain the data obtained after measuring the length and angle of each part of the ornament. The length and width of the ornament were measured using a raffia string and a ruler. While the angle of the ornament is measured using a protractor. The measurement results of the ornament's length, width, and angles are recorded in the observation sheet. The measurement process is presented in Picture 6a. The measurement results of length and angle measurements are represented again in the millimeter block book, as shown in Picture 6b. Representation is necessary to ensure the similarity of the measurement results with the shape of the ornament.



(a) (b)

Picture 6. (a) Ornament length measurement process, (b) Sketch of the ornament measurement result

The results of measuring the length of the ornament are represented in sketch form, as shown in Picture 6b. Then the researcher gave the name of each corner in the sketch. Giving a name is done to make it easier for researchers to ensure the similarity of the length measurement results with the shape of the ornament. The length of each part of the ornament is a multiple of 14. Thus, the ratio of the length of the ornament was found. The ratio search aims to lighten the computer's workload during the visualization and simplify coding with the l-system. The results of the length measurements and the ratios found are presented in Table 1.

Table 1. Length measurement results of Tian Ti Pagoda ornaments

Measured part	Size	Scaling with 14 cm
Ornament length	224 cm	1:16
Ornament width	112 cm	1:8
BC, CG, JK	14 cm	1:1
AB, CD, DE, EF, CF	28 cm	1:2
KL, LM	35 cm	1:2,5
GH, OP, PQ, QR	42 cm	1:3
NO	49 cm	1:3,5
$HI, IJ, MN, RS, ST, TU, UR$	56 cm	1:4

Based on the measurement results represented in sketch form in Picture 6b, the researcher found that the angles on each part of the ornament were 90^o or right angles. The measurement results are presented in Table 2.

Table 2. Length measurement results of Tian Ti Pagoda ornaments

Measured angle	The magnitude of The Angle
$\angle A, \angle B, \angle C, \angle D, \angle E, \angle F, \angle G, \angle H, \angle O, \angle P, \angle Q, \angle R, \angle S, \angle T, \angle U$	90^o

Fractal Modeling Results with L-System

Fractal modeling of Tian Ti Pagoda ornaments is performed with the Lindenmayer system on a two-dimensional plane. The definitions of symbols and parameters in the L-system are summarized in Table 3.

Table 3. Symbol and parameter definitions in L-System

Parameters	Symbol	Meaning
Direction	F	Draw forward by 1 unit.
	$+(\alpha)$	Rotates counterclockwise with a rotation matrix $R(\alpha)$ of (α) degrees
	$-(\alpha)$	Rotate clockwise with a rotation matrix $R(\alpha)$ of (α) degrees
Angle	Y	Rotate by 90 degrees
Length	$O(s)$	Draw forward by 14 cm.
	$P(s)$	Draw forward by 28 cm.
	$Q(s)$	Draw forward by 56 cm.
	$R(s)$	Draw forward by 42 cm.
	$S(s)$	Draw forward by 70 cm.

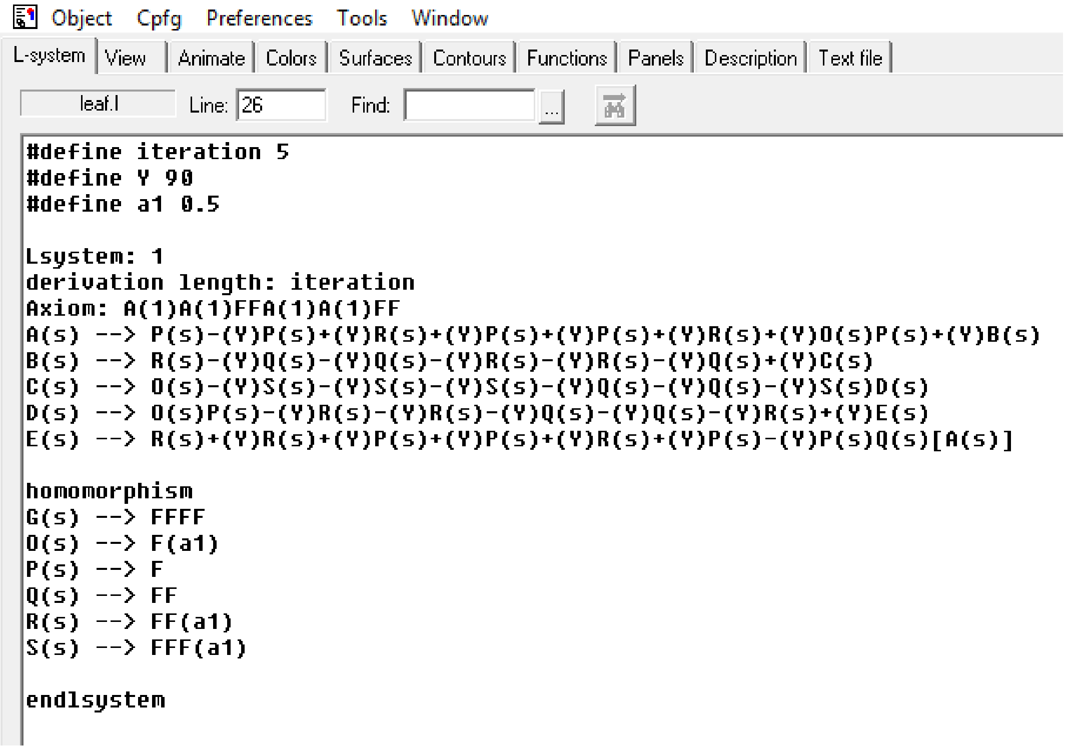
After the symbols and parameters are determined, the next step is to compile the L-system production rules based on the observation results, parameters, and symbols assembled with the help of the L-Studio application. The following are the production rules made for the Tian Ti Pagoda ornament.

Generator:
$w = A(1); Y = 90; a1 = 0.5$

Number of iterations: 5
p1 : $A(s) \rightarrow P(s) - (Y)P(s) + (Y)R(s) + (Y)P(s) + (Y)P(s) + (Y)R(s) + (Y)R(s) + (Y)B(s)$
p2 : $B(s) \rightarrow R(s) - (Y)Q(s) - (Y)Q(s) - (Y)R(s) - (Y)R(s) - (Y)Q(s) + (Y)C(s)$
p3 : $C(s) \rightarrow O(s) - (Y)S(s) - (Y)S(s) - (Y)S(s) - (Y)Q(s) - (Y)Q(s) - (Y)S(s)D(s)$
p4 : $D(s) \rightarrow O(s)P(s) - (Y)R(s) - (Y)R(s) - (Y)Q(s) - (Y)Q(s) - (Y)R(s) - (Y)E(s)$
p4 : $E(s) \rightarrow R(s) + (Y)R(s) + (Y)P(s) + (Y)P(s) + (Y)P(s) + (Y)R(s) + (Y)P(s) - (Y)P(s)Q(s)[A(s)]$

Homomorphism: 6
$O(s) \rightarrow F(a1)$
$P(s) \rightarrow F$
$Q(s) \rightarrow FF$
$R(s) \rightarrow FF(a1)$
$S(s) \rightarrow FFF(a1)$

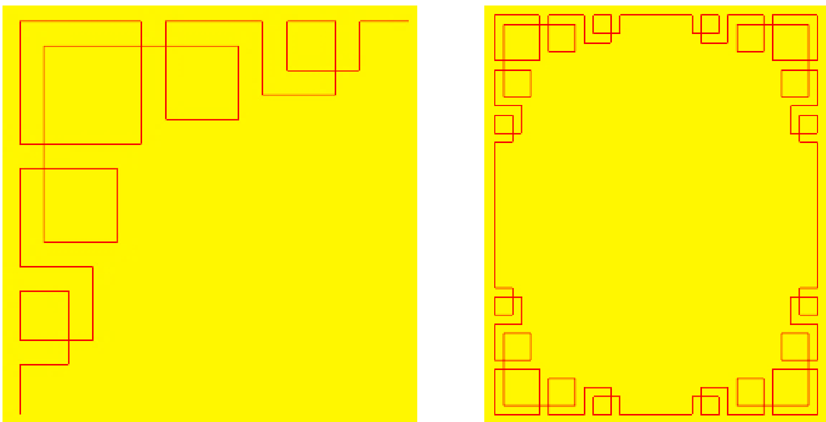
The screen display of the Tian Ti Pagoda ornament production rules in the L-Studio application is as follows.




```
#define iteration 5
#define Y 90
#define a1 0.5

Lsystem: 1
derivation length: iteration
Axiom: A(1)A(1)FFA(1)A(1)FF
A(s) --> P(s)-(Y)P(s)+(Y)R(s)+(Y)P(s)+(Y)P(s)+(Y)R(s)+(Y)O(s)P(s)+(Y)B(s)
B(s) --> R(s)-(Y)Q(s)-(Y)Q(s)-(Y)R(s)-(Y)R(s)-(Y)Q(s)+(Y)C(s)
C(s) --> O(s)-(Y)S(s)-(Y)S(s)-(Y)S(s)-(Y)Q(s)-(Y)Q(s)-(Y)S(s)D(s)
D(s) --> O(s)P(s)-(Y)R(s)-(Y)R(s)-(Y)Q(s)-(Y)Q(s)-(Y)R(s)+(Y)E(s)
E(s) --> R(s)+(Y)R(s)+(Y)P(s)+(Y)P(s)+(Y)R(s)+(Y)P(s)-(Y)P(s)Q(s)[A(s)]

homomorphism
G(s) --> FFFF
O(s) --> F(a1)
P(s) --> F
Q(s) --> FF
R(s) --> FF(a1)
S(s) --> FFF(a1)

endlsystem
```

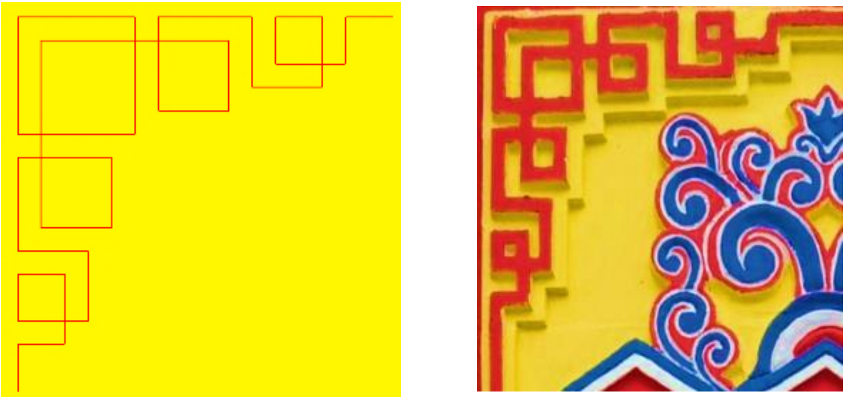
Picture 7. Display of production rules in the L-Studio application.

The visualization results of the Tian Ti Pagoda ornament are based on the length and angle measurements of the modeled object. Then it is written in the Lindenmayer system production rules. Furthermore, the writing of the l-system is visualized using the L-studio application. The University of Cagliari designed and developed the application to model and visualize l-system rules (Prusinkiewicz & Lindenmayer, 2012). The visualization results are in two-dimensional form. That is because the direction parameters are + (α) and $-(\alpha)$, which are limited to the Cartesian plane. Thus, the visualization results can only be seen from one point of view. The following are the visualization results of the Tian Ti Pagoda ornament production rules using the L-system.

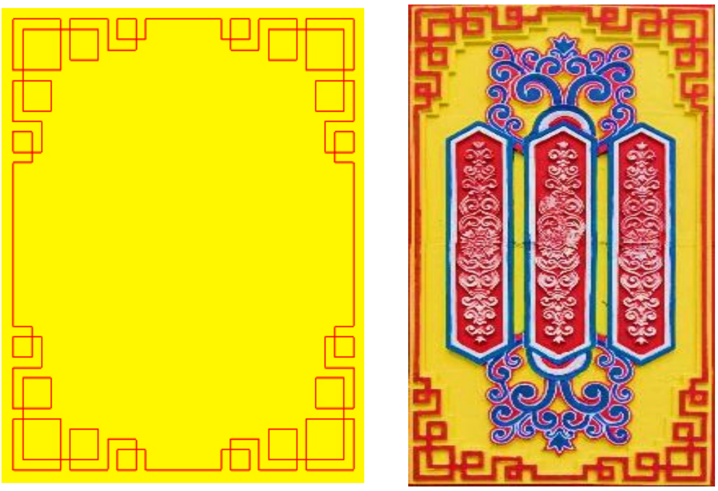


Picture 8. The visualization result of the Tian Ti Pagoda ornament in L-Studio.

After visualization with the help of L-studio, the visualization results are rechecked. Every detail of the visualization of Tian Ti Pagoda ornaments is enlarged, rotated, and compared with the original image. That aims to ensure that there are no errors in the visualization results. If there are errors, changes are made to the production rule components. The iterations used are limited to 5 iterations to prevent errors when running on L-studio visualization. The following results compare the visualization results with the original object.



Picture 9. Comparison of some results of fractal visualization of Tian Ti Pagoda ornaments with the original object.



Picture 10. Comparison of the overall results of fractal visualization of Tian Ti Pagoda ornaments with the original object.

Based on the l-system production rules and visualization results on the Tian Ti pagoda ornaments, it was found that these ornaments can be studied mathematically using the concept of fractal geometry. This result is in line with research by Lee & Tiong (2013), who found that The concept of Lattice Theory is also applied to Chinese-style ornaments. Furthermore, Chinese ornaments based on swastika or wave styles can be reconstructed using fractal geometry to resemble their original form (Dye, 2012).

Some literature on Chinese ornaments shows that several types of ornament have looping, recursive, geometric, and opposite characteristics (Dye, 2012; Lee & Tiong, 2013; Wen, 2011). Furthermore, Xu dkk. (2020) said Chinese ornaments have symmetrical, balanced, and dynamic shapes. Symmetrical nature makes ornaments have the same shape and color. The dynamic nature makes the ornament look opposite, centrifugal and can be combined with other elements. While the balanced nature makes the ornament have a center point that balances other elements. That was reinforced by the results of the interview with Mrs. Jing-Jing, the manager of the Tian Ti Pagoda. He explained that the ornaments on the Pagoda were replicas of Chinese, so the colors, shapes, sizes, and regularity of the ornaments came from Chinese culture.

Based on Dye (2012), the shape of this Chinese ornament contains a wave shape and a shape similar to a swastika. The waves formed are squares connected and opposite each other. In comparison, the swastika-like shape is at the intersection of the ornaments. Swastika comes from the Sanskrit 'su', which means good and be (Shomakhmadov, 2012). This symbol means good if the rotating side is clockwise and bad if the rotating side is counterclockwise (Dye, 2012; Wen, 2011). In Buddhism, the swastika is a sacred symbol, described as an accumulation of auspicious signs having ten thousand properties. It is also considered a symbol or seal of the Buddha's heart (Lee-Kalisch, 2018). That is in line with the interview results, the paired and opposite waves are inspired by the yin-yang symbol, which means balance and complements each other.

Furthermore, Wave and Unlike Swastika-style ornaments, are often placed on space-filling or meandering cornices, such as on the sides or edges of windows (Nassar & Sabbagh, 2016). Meander ornaments containing swastikas symbolize the heart of the Buddha in Buddhist paintings. It emphasizes the meaning of infinity and the power of reincarnation in various ways (Lee-Kalisch, 2018). In addition, meanders in Chinese ornaments symbolize luck, breadth, and depth. It can be classified into those that invoke the traditional "Five Fortunes", which represent the desire for honor, and those that reflect purity, elegance, and aspiration (Wen, 2011).

Chinese ornaments' geometric and endlessly winding patterns signify wealth, good fortune, and infinite rank. It has an attractive, regular, and uniform shape yet is capable of various changes (Dye, 2012; Wen, 2011). In traditional Chinese buildings, this chain pattern has meanings such as continuous and endless or endless happiness and longevity (Lee-Kalisch, 2018). The interview results also show that the continuous shape of the ornament is a manifestation of infinite gratitude.

Mathematically, geometric shapes, endlessly winding, and self-similar shapes are properties of fractal geometry (Abu-Elwan, 2014; Chowdary dkk., 2015). In other words, the Chinese ornaments on Tian Ti Pagoda already have fractal shapes. That is reinforced by the visualization results using the Lindenmayer system, which found the existence of fractal shapes. Furthermore, these results show that fractal geometry is not only found in nature or constructed mathematically but also in cultural elements that society has long studied.

The existence of fractal shapes in Tian Ti Pagoda ornaments can allow other researchers to explore different fractal shapes. In addition, these results can be redeveloped to be integrated and applied in learning non-Euclidean geometry. So that students can be introduced to fractal geometry learning resources that can be found in the culture of society. Furthermore, the results of this study can be brought into the realm of learning by asking students to look for modifications to the fractal shape of the Tian Ti Pagoda ornament. Thus, learning fractal geometry can lead to creative thinking wrapped in the knowledge of society's culture.

Conclusions and Suggestions

Based on the results and discussion, nuanced Chinese ornaments on Tian Ti Pagoda can be concluded that there are fractal geometry shapes. The length and angle of each part of the ornament influence the fractal form. The Lindenmayer system technique takes five iterations with a slope of 90 degrees and a ratio of 14 to visualize the fractal shape of the Tian Ti pagoda.

This research is still limited in exploring Tian Ti Pagoda ornaments, so the concept of fractal geometry needs to be explored in other Chinese ornaments. In addition, the method used to see the fractal shape is limited to the deterministic Lindenmayer system (D0L-system) method, so the visualized results are discrete. The researcher suggests studying the forms of non-Euclid geometry in other cultures in other ways, such as using lattice theory, graph theory, and stochastic l-system. We also hope this research will be used in lectures, such as computational geometry, dynamic systems, and mathematical modelling classes.

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