

Fractals:

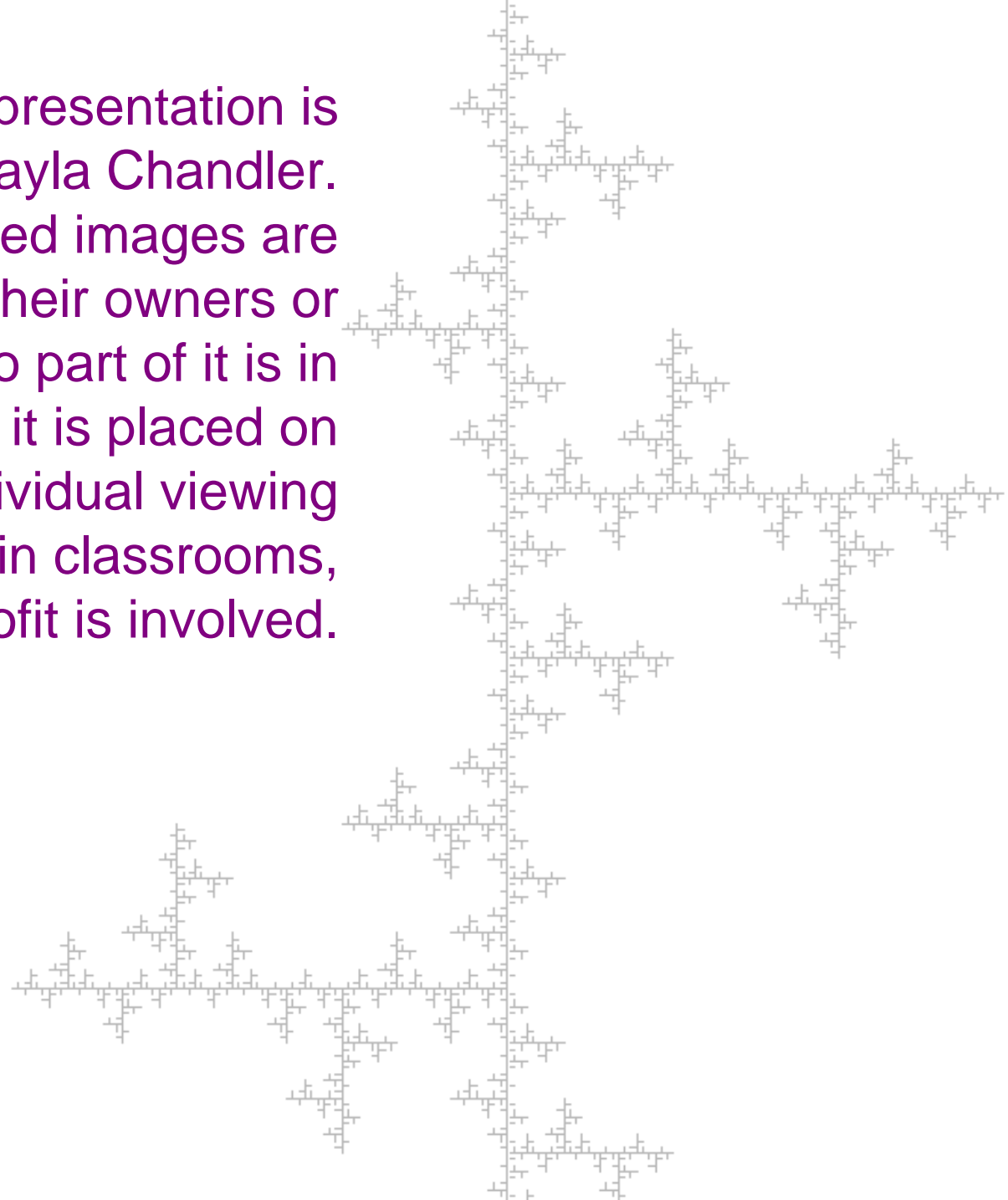


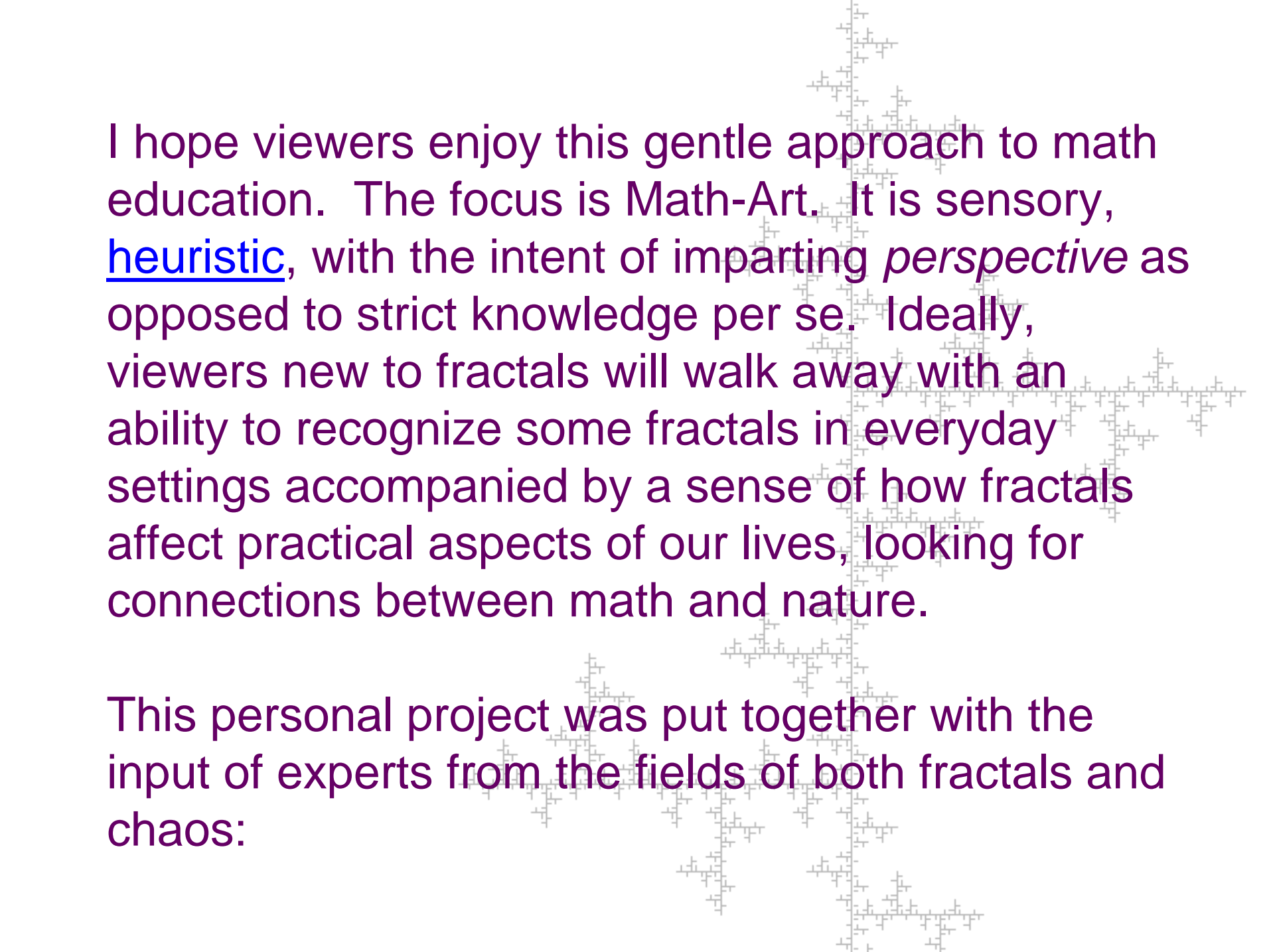
an Introduction through Symmetry

for beginners to fractals,
highlights magnification symmetry
and fractals/chaos connections

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I hope viewers enjoy this gentle approach to math education. The focus is Math-Art. It is sensory, heuristic, with the intent of imparting *perspective* as opposed to strict knowledge per se. Ideally, viewers new to fractals will walk away with an ability to recognize some fractals in everyday settings accompanied by a sense of how fractals affect practical aspects of our lives, looking for connections between math and nature.

This personal project was put together with the input of experts from the fields of both fractals and chaos:

Academic friends who provided input:

Don Jones

Department of Mathematics & Statistics
Arizona State University

Reimund Albers

Center for Complex Systems & Visualization (CeVis)
University of Bremen

Paul Bourke

Centre for Astrophysics & Supercomputing
Swinburne University of Technology

A fourth friend who has offered feedback, whose path I followed in putting this together, and whose influence has been tremendous prefers not to be named yet must be acknowledged. You know who you are. Thanks. 😊

First discussed will be three common types of symmetry:

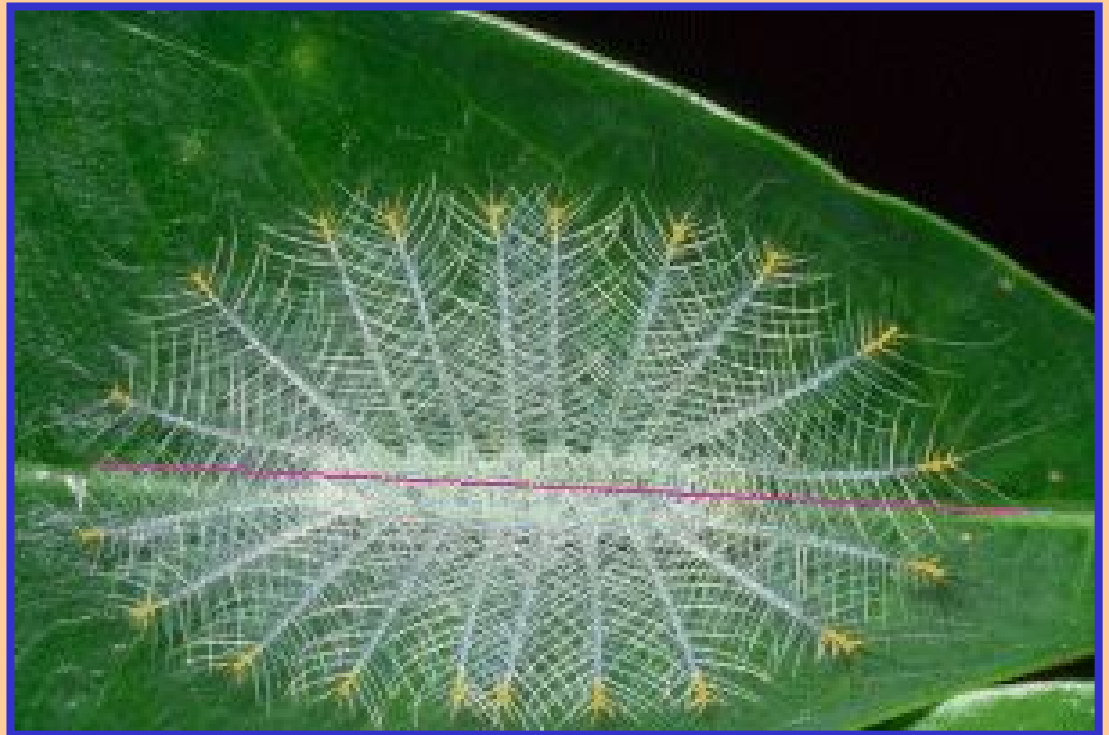
- Reflectional (Line or Mirror)
- Rotational (N-fold)
- Translational

and then: the Magnification
(Dilatational a.k.a. Dilational)
symmetry of fractals.

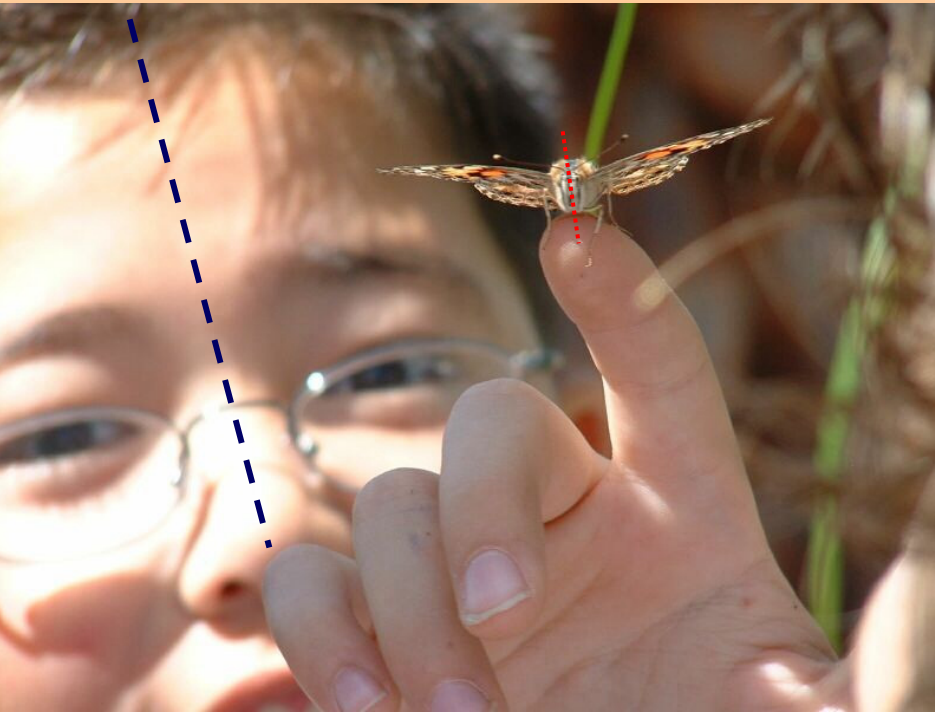
Reflectional (aka Line or Mirror) Symmetry

A shape exhibits reflectional symmetry if the shape can be bisected by a line L , one half of the shape removed, and the missing piece replaced by a reflection of the remaining piece across L , then the resulting combination is (approximately) the same as the original.¹

In simpler words, if you can fold it over and it matches up, it has **reflectional symmetry**. This leaf, for instance, and the butterfly caterpillar sitting on it, are roughly symmetric. So are human faces. **Line symmetry** and **mirror symmetry** mean the same thing.



From “An Intuitive Notion of Line Symmetry”



The butterfly and the children have lines of reflection symmetry where one side mirrors the other.

Taken at the same time at the [Desert Botanical Gardens Butterfly Pavilion](#), the little butterfly is a Painted Lady (*Vanessa, cardui*). Its host plant is (*Thistles, cirsium*).





These images have
lines of symmetry
at the edge of the
water.

Here is a link to a [PowerPoint presentation](#) “created by Mrs. Gamache using the collection of web pages by the Adrian Bruce and students of 6B.”

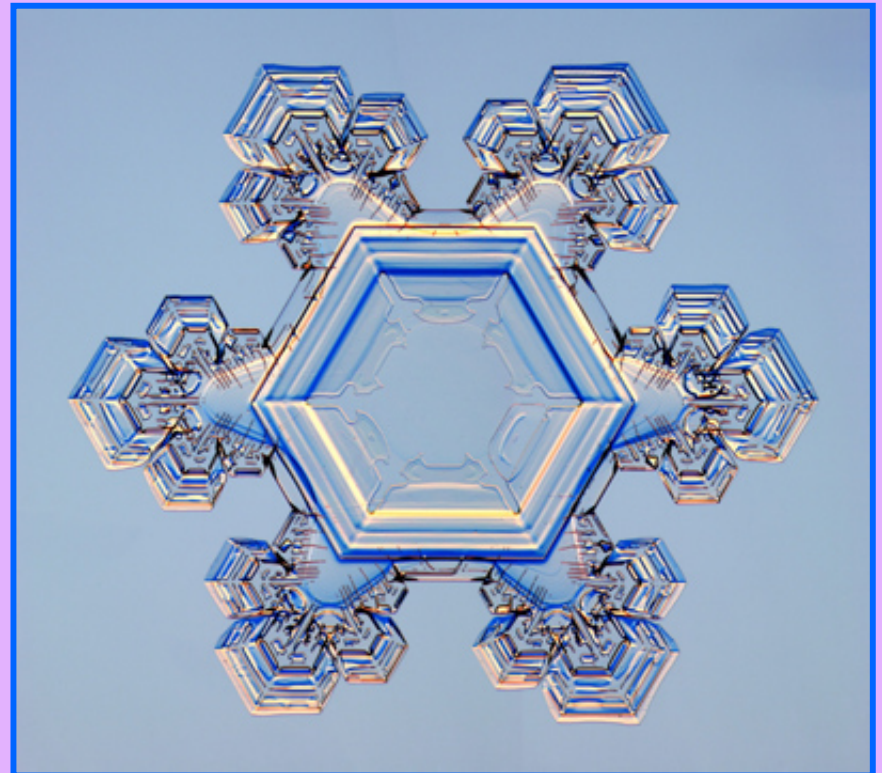
This site lets you [create your own symmetry patterns!](#) Choose your type and color, then start moving the mouse and clicking.




Rotational (N-fold) Symmetry

A shape exhibits rotational symmetry if rotation about some center point returns the shape to its original configuration.²

Libbrecht of Caltech discusses symmetry of ice crystals and snowflakes



Real snowflake image taken by Kenneth Libbrecht using a special photo microscope



These blooms have 5-fold rotational symmetry. They can be turned 5 times to leave the figure unchanged before starting over again.

A pentagon also has 5-fold symmetry.

The butterfly is a Spicebush Swallowtail (*Papilio troilus*).



An example of 4-fold rotational symmetry, a property shared by the square.



5-fold or 6-fold
symmetry here



This flower has
21-fold rotational
symmetry.



The tiny blooms have 4-fold
symmetry. Question: does
the spherical bloom they sit
on have n-fold symmetry?

Butterfly names



Julia, (*Dryas, julia*)

5-fold or 6-fold symmetry here



This flower has 21-fold rotational symmetry.

Great Southern Whites (*Ascia monuste*)



The tiny blooms have 4-fold symmetry. Question: does the spherical bloom they sit on have n-fold symmetry?

Zebra Longwings (*Heliconius, charitonius*)

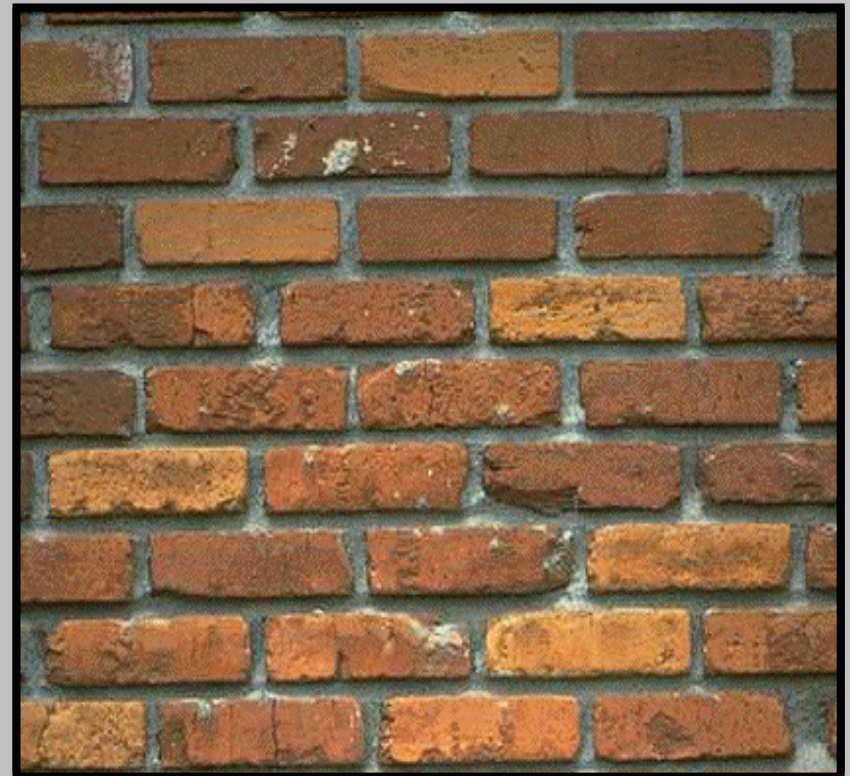
Translational Symmetry

A shape exhibits translational symmetry if displacement in some direction - horizontal or vertical, for example - returns the shape to (approximately) its original configuration.³

The bricks in the image have translational symmetry.

Also, the image of the bricks will have translation symmetry when sliding, provided there is no rotation during the move.

Orientation must be preserved while translating.



Magnification (Dilatational) Symmetry

Less familiar is symmetry under magnification:
zooming in on an object leaves the shape
approximately unaltered.⁴

Zooming in on a fractal object
leaves the shape
approximately unaltered.

Fractals exhibit magnification symmetry.

Types of Fractals highlighted:

- Natural
- Geometric
- Complex and Random

Brief discussion: Frames of Reference

and examples of:

Exponential Growth

Fractals Across the Disciplines

Natural Fractals

Multifractals

Chaos

Natural fractals have a limited number of stages of growth, and the growth between stages shows variation. They have connections to Multifractals and Chaos theory.

Fractals in the Biological Sciences

by N. C. Kenkel and D. J. Walker

University of Manitoba

Quantitative Plant Ecology Laboratory

below is an excerpt from their web page

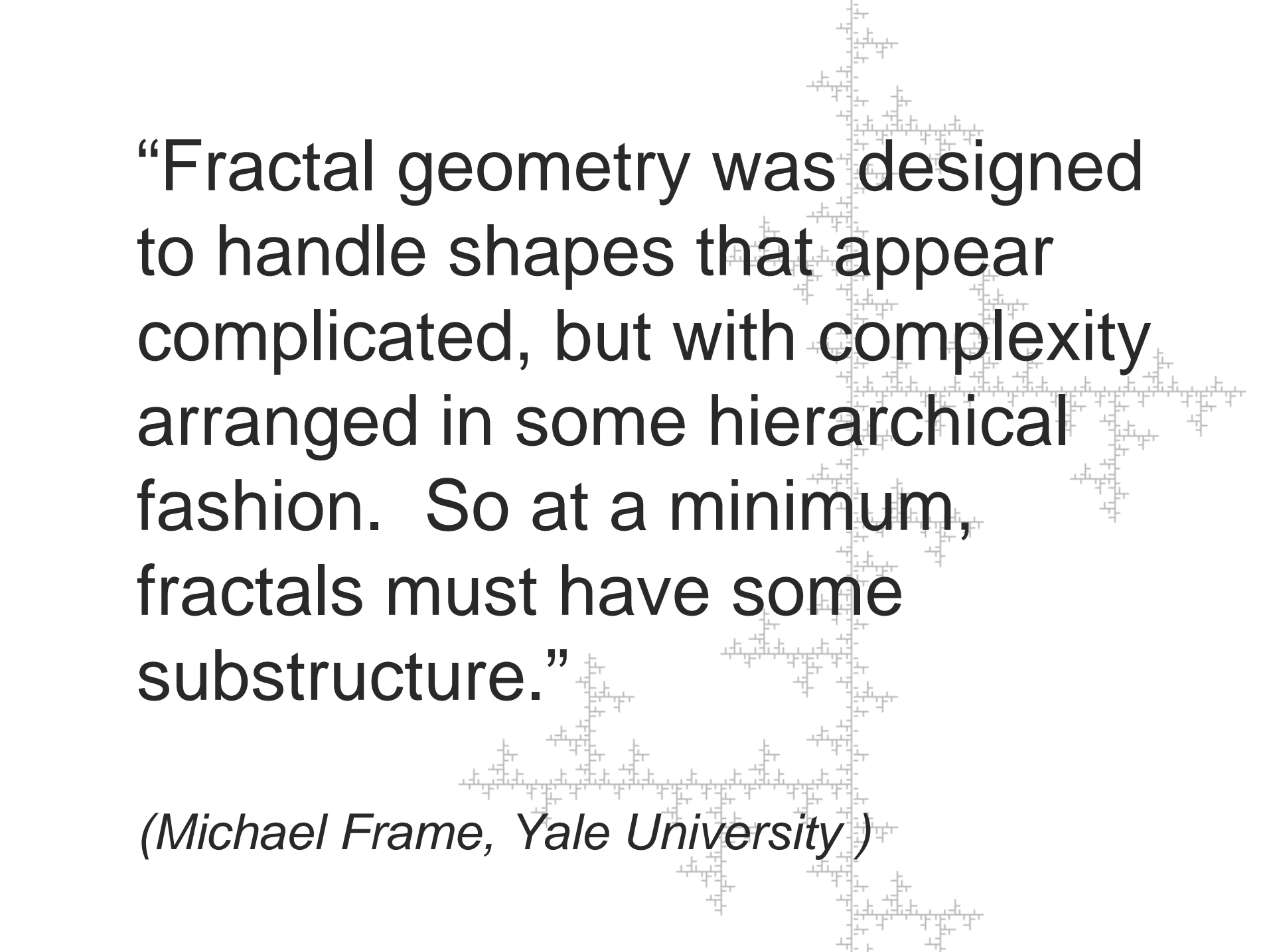
Section 5.7 Chaos and Time Series Analysis:

“Chaos, which is closely related to fractal geometry, refers to a kind of constrained randomness (Stone and Ezrati 1996).

Wherever a chaotic process has shaped an environment, a fractal structure is left behind.”



Photo by Gayla Chandler
Post Processing by [Kim Letkeman](#)



“Fractal geometry was designed to handle shapes that appear complicated, but with complexity arranged in some hierarchical fashion. So at a minimum, fractals must have some substructure.”

(Michael Frame, Yale University)

One necessary condition for fractal substructure is the same or a highly similar shape between a minimum of 3 stages of growth (there exists disagreement on this, especially between disciplines).

The entire fern family reveals self-similarity: successive stages of growth that closely resemble earlier stages.

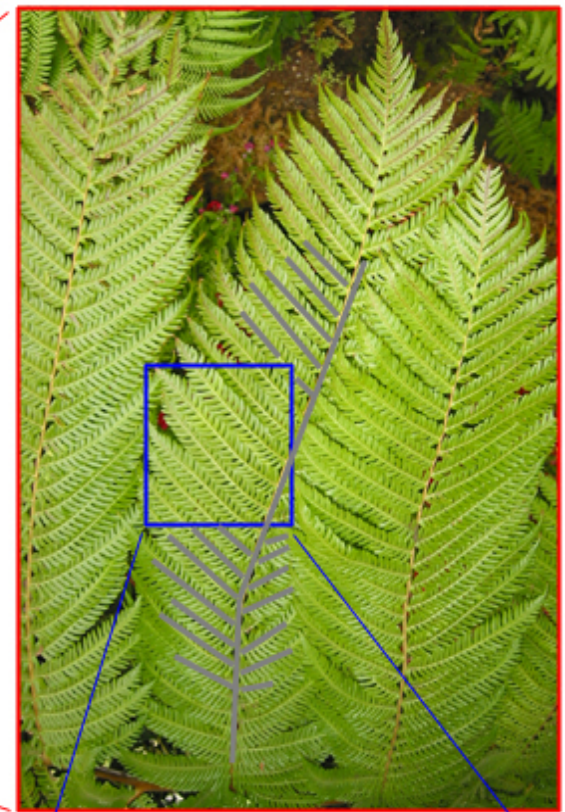


Image from Paul Bourke's [Self-Similarity](#) page.



Photo courtesy of Pbase artist [Ville Vels](#) of Estonia



← Icicles made of icicles

Photo courtesy of Pbase artist [Ville Vels](#) of Estonia



Repeating
shapes on
different scales.

Photo courtesy of Pbase artist [Ville Vels](#) of Estonia



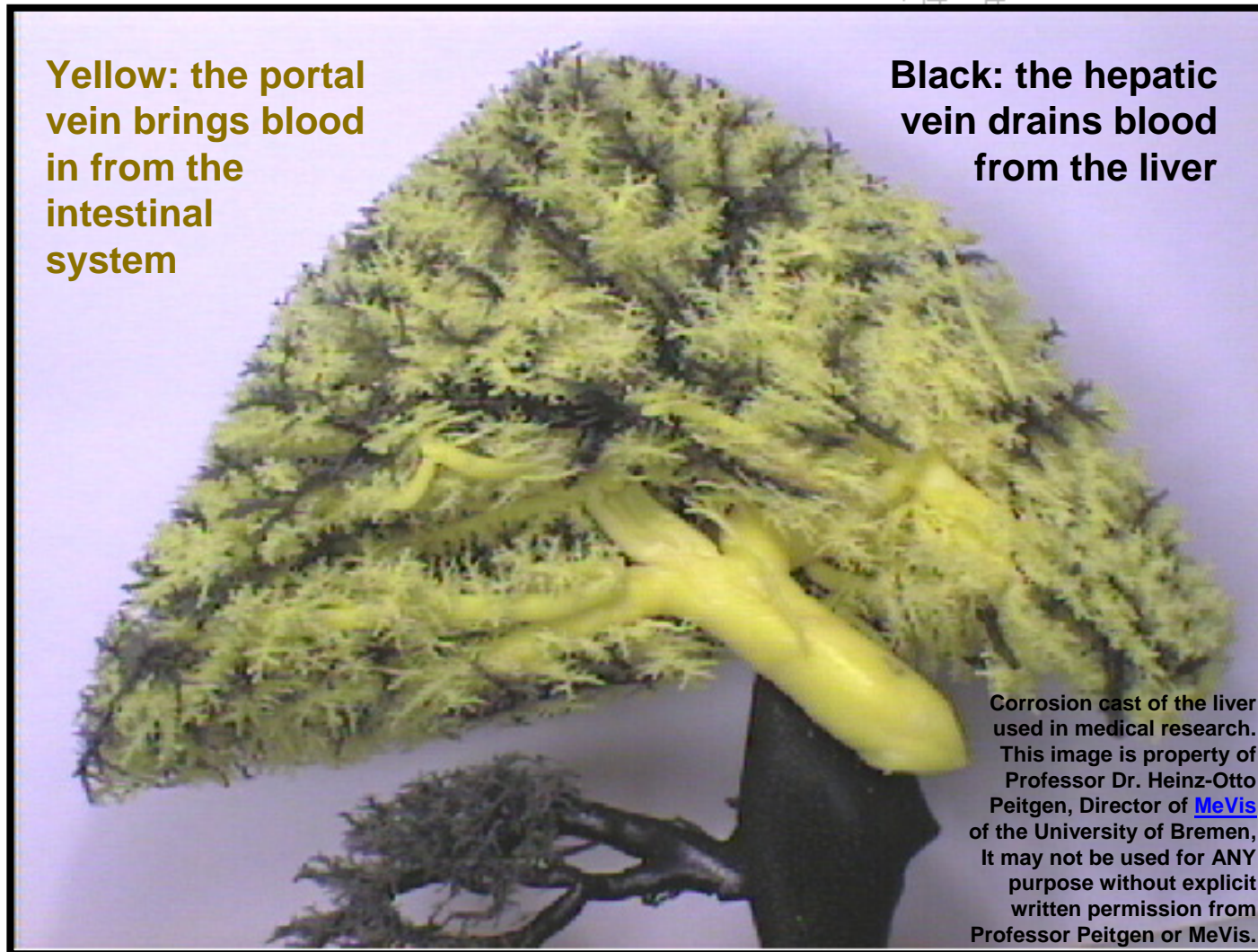
Photo courtesy of Pbase artist [Ville Vels](#) of Estonia

Branching Patterns



This corrosion cast of the liver used in medical research reveals [fractal branching](#) as do several [body organs](#). Most branching in nature is fractal: [leaf veins](#) and [rivers](#), our [circulatory system](#) and [lightning](#), to name a few.

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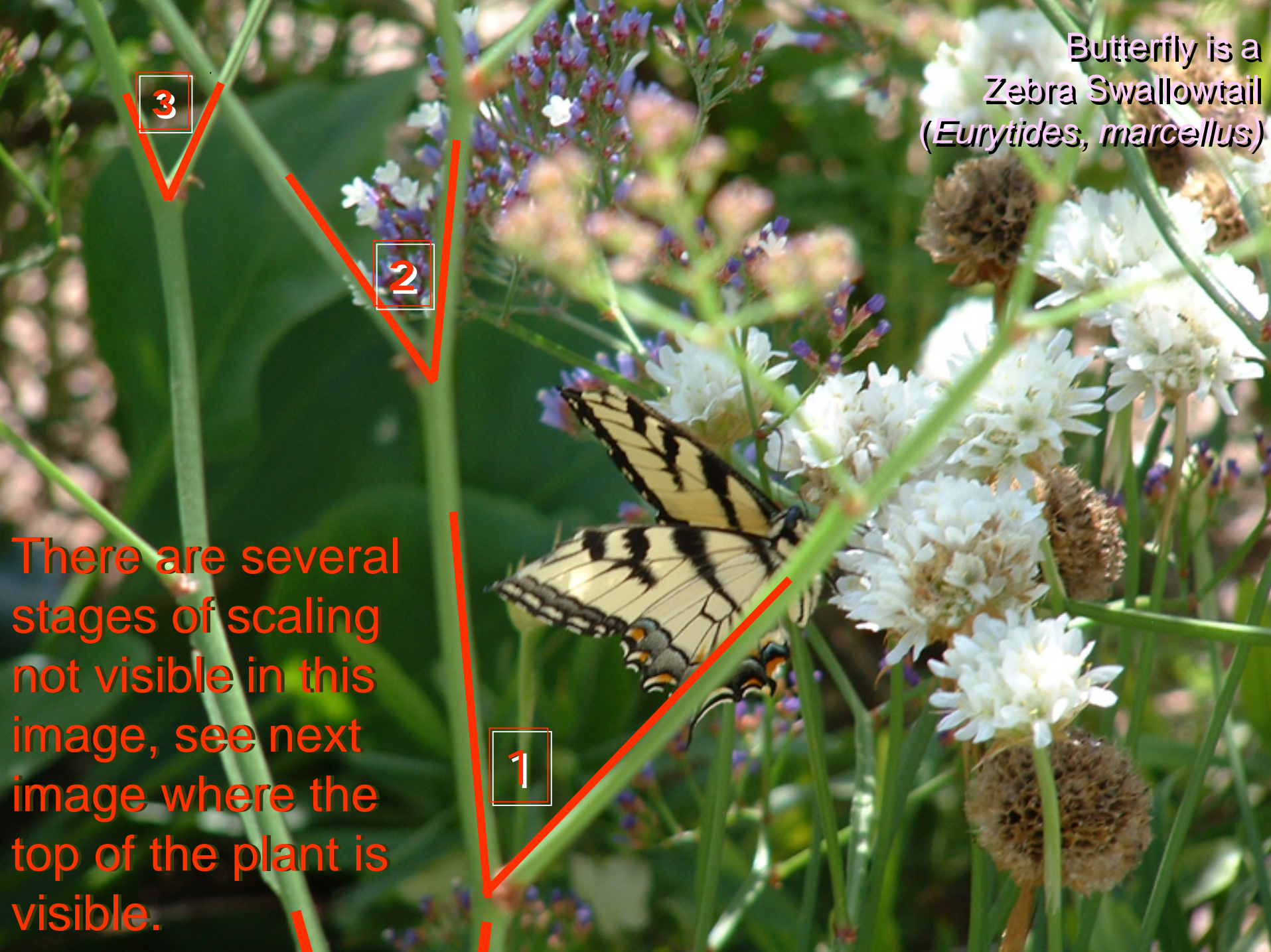
Butterfly is a
Zebra Swallowtail
(*Eurytides, marcellus*)

3

2

1


There are several stages of scaling not visible in this image, see next image where the top of the plant is visible.



The butterfly is a
Great Southern White

The scaled
branching extends
upward throughout
the plant. A small
branch, if magnified,
would look like a
larger branch.



A photograph of a butterfly on a purple flower cluster. The butterfly is white with black markings on its wings. The flower cluster is composed of many small purple flowers. Three colored outlines (pink, yellow, and cyan) are drawn over the flower cluster, highlighting the fractal-like structure of the plant. The pink outline follows the main stem and the overall shape of the flower cluster. The yellow outline follows a smaller branch of the cluster. The cyan outline follows an even smaller branch, illustrating how the structure of smaller sections dictates the shape of larger sections.

Also notice how entire sections of the plant resemble each other on different scales. The structure of smaller sections dictates the shape of larger sections.

Fractal branching is captured in shadow below. From this view, again notice how the parts resemble the whole.



A Painted Lady is present!

The plant in the previous slides resembles this computer-generated binary fractal tree.

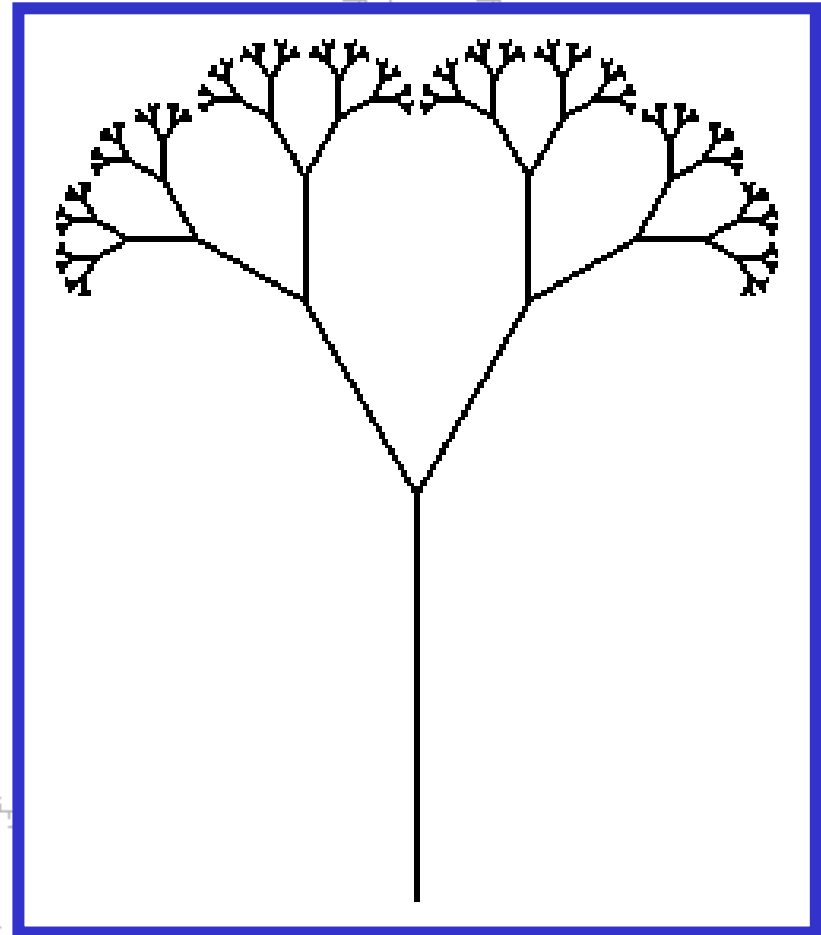



Image by Don West



Photograph courtesy of Clive Pierson, taken in Ireland.

A photograph of a winter landscape. A snow-covered path leads through a forest of bare trees. In the distance, three people are walking away from the camera. The sky is clear and blue. The trees have a complex, branching structure that illustrates the concept of fractals.

Similarity in tree branches can be seen in the shapes of clumps of tree, intersections of branches, the flow of limbs... Repeating a simple pattern throughout growth yields a complex structure with magnification symmetry, a structure made of parts that are similar to the whole: a **fractal structure.**

Photograph courtesy of Clive Pierson, taken in Ireland.



Photograph courtesy of Clive Pierson, taken in Ireland.



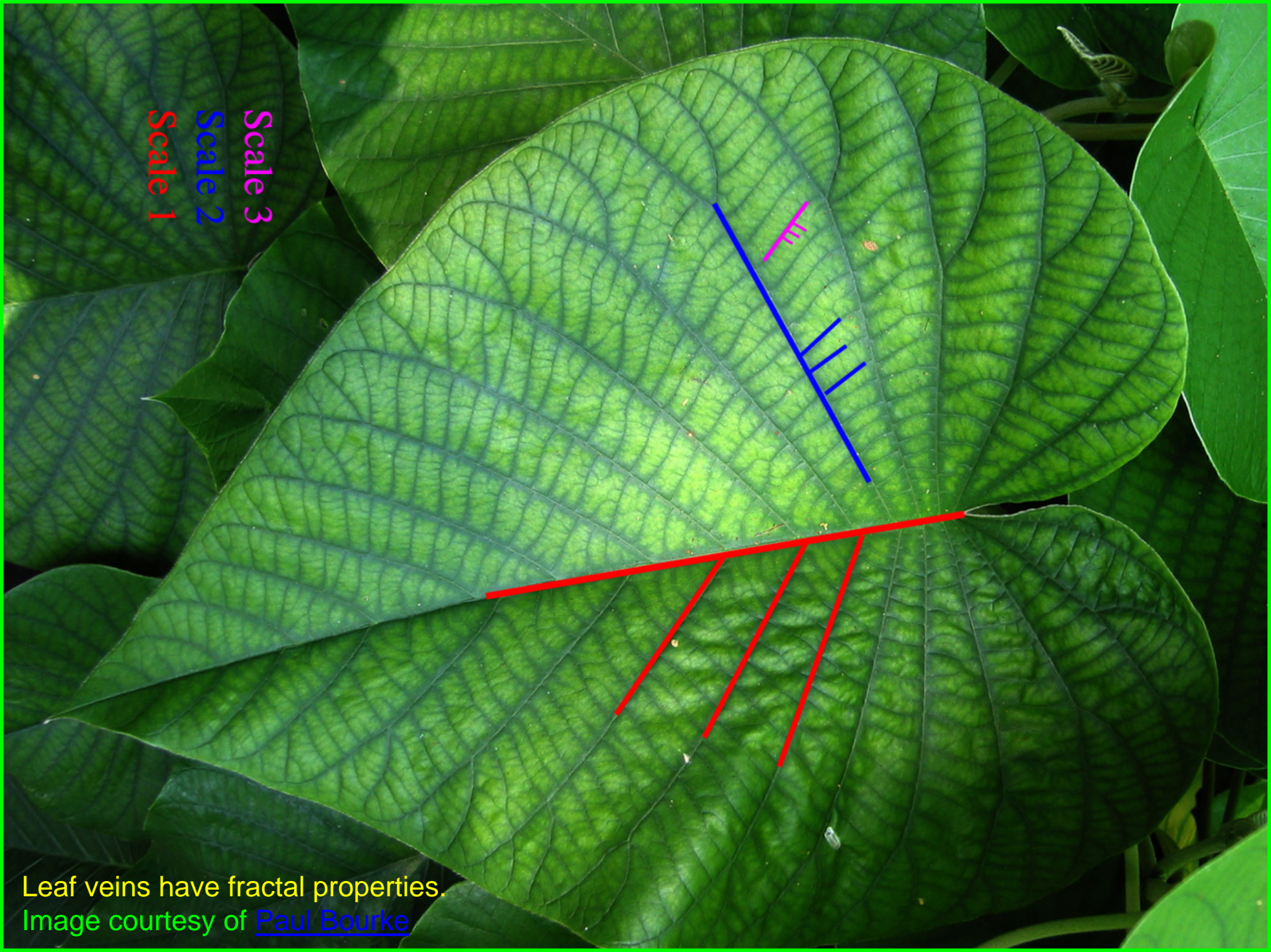
Photograph courtesy of Clive Pierson, taken in Ireland.



Photograph courtesy of Clive Pierson, taken in Ireland.



Photograph courtesy of Clive Pierson, taken in Ireland.



Scale 3
Scale 2
Scale 1

Leaf veins have fractal properties.
Image courtesy of [Paul Bourke](#)

With fractals, the structure behind small sections dictates overall shape.

We have seen [empirical](#) verification of this in previous examples, how bigger shapes were [aggregations](#) of the smaller shapes that made them up. This is also true of clouds, mountains, ocean waves, lightning, and many other aspects of nature. An ocean wave is made up of a lot of little waves, which are in turn made up of yet smaller waves. This is why fractal equations tend to be simple. Tremendous complexity can result from [iterating](#) simple patterns.

Of those aspects that have an embedded fractal structure, their fractal aspect only describes properties of shape and complexity. Read this [Word of Caution](#) from Nonlinear Geoscience: Fractals. They refer to randomness that is taken into account in [Multifractal theory](#), which has ties to [Chaos theory](#) and [Nonlinear Dynamics](#).

The Yale Fractal Geometry website points out [Common Mistakes](#) in Finding Fractals. Also view this [Introduction to Fractals](#) PowerPoint presentation out of Florida Atlantic University by Liebovitch and Shehadeh that makes many fractal/nonfractal comparisons. Read a paper from Complexity International about language issues with regard to fractals: [Is There Meaning In Fractal Analysis?](#)



This is a Sweet Acacia ([Acacia, smallii](#)) tree. Its unbloomed flower appears to be a sphere made up of [smaller-scale](#) spheres, but take a closer look:

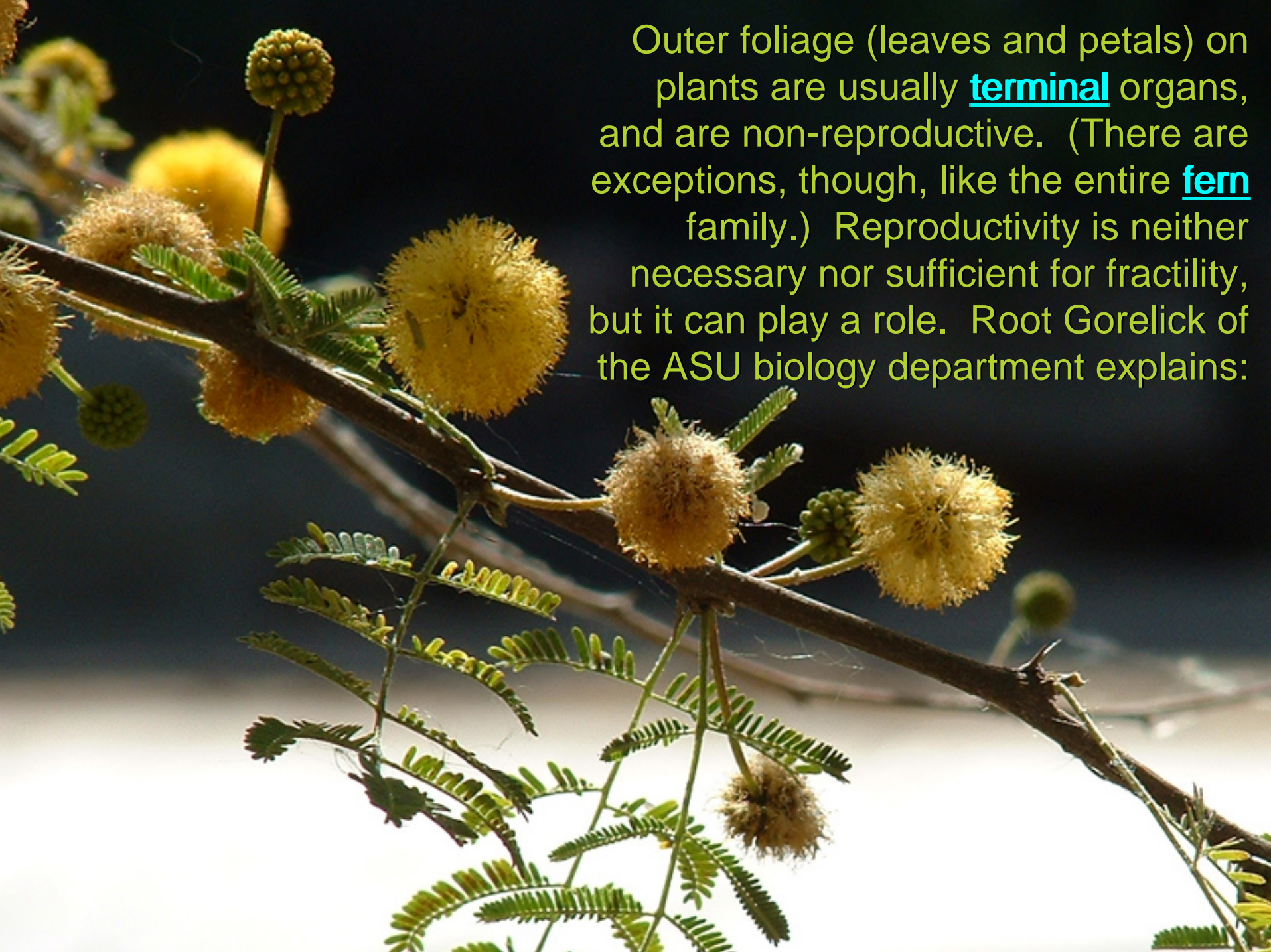



This is a Sweet Acacia ([Acacia, smallii](#)) tree. Its unbloomed flower appears to be a sphere made up of [smaller-scale](#) spheres, but take a closer look:



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Outer foliage (leaves and petals) on plants are usually terminal organs, and are non-reproductive. (There are exceptions, though, like the entire fern family.) Reproductivity is neither necessary nor sufficient for fractility, but it can play a role. Root Gorelick of the ASU biology department explains:





Outer foliage (leaves and petals) on plants are usually **terminal** organs, and are non-reproductive. (There are exceptions, though, like the entire **fern** family.) Reproductivity is neither necessary nor sufficient for fractality, but it can play a role. Root Gorelick of the ASU biology department explains:

“Leaves are terminal organs, hence don't reproduce miniature copies of themselves as do stems, roots, and many reproductive structures. Therefore, I expect leaves to be least fractal of these organs.”
(Root Gorelick)

Geometric Fractals

I like to compare Geometric fractals to objects/systems in a [vacuum](#) in physics. They are, as their name suggests, geometric constructs, perfect (Ideal) systems exempt from internal deviations or potential changes from outside influences (other than human error in constructing them).

I haven't included Complex fractals such as the Mandelbrot Set and Julia Sets in the Geometric fractals category. Complex fractals are mentioned later.

The Sierpinski Tetrahedron

Fractal type: Geometric

Tetrahedra are increasing in number in powers of 4
Tetrahedra are decreasing in edge-length in powers of $\frac{1}{2}$
Volume is decreasing in powers of $\frac{1}{8}$

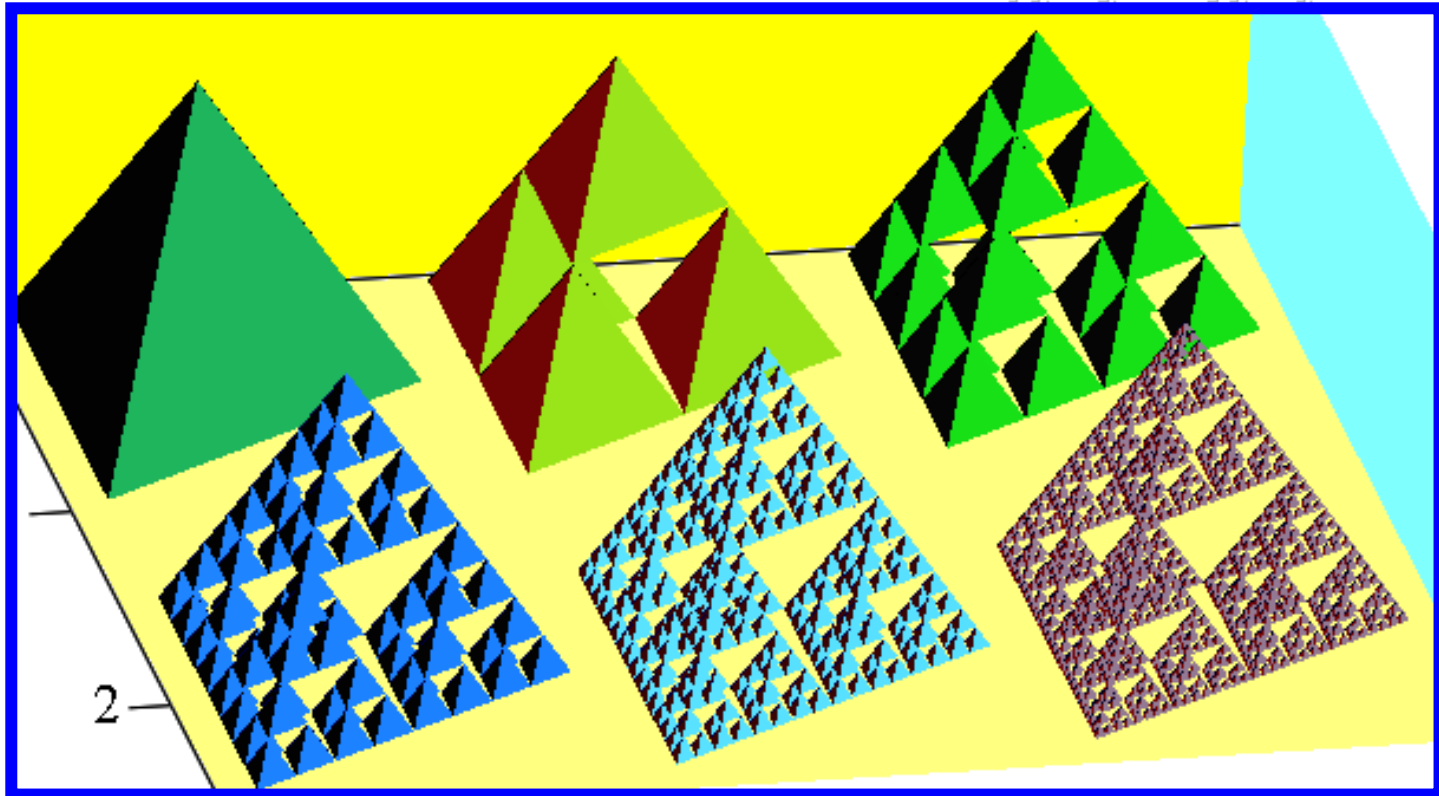
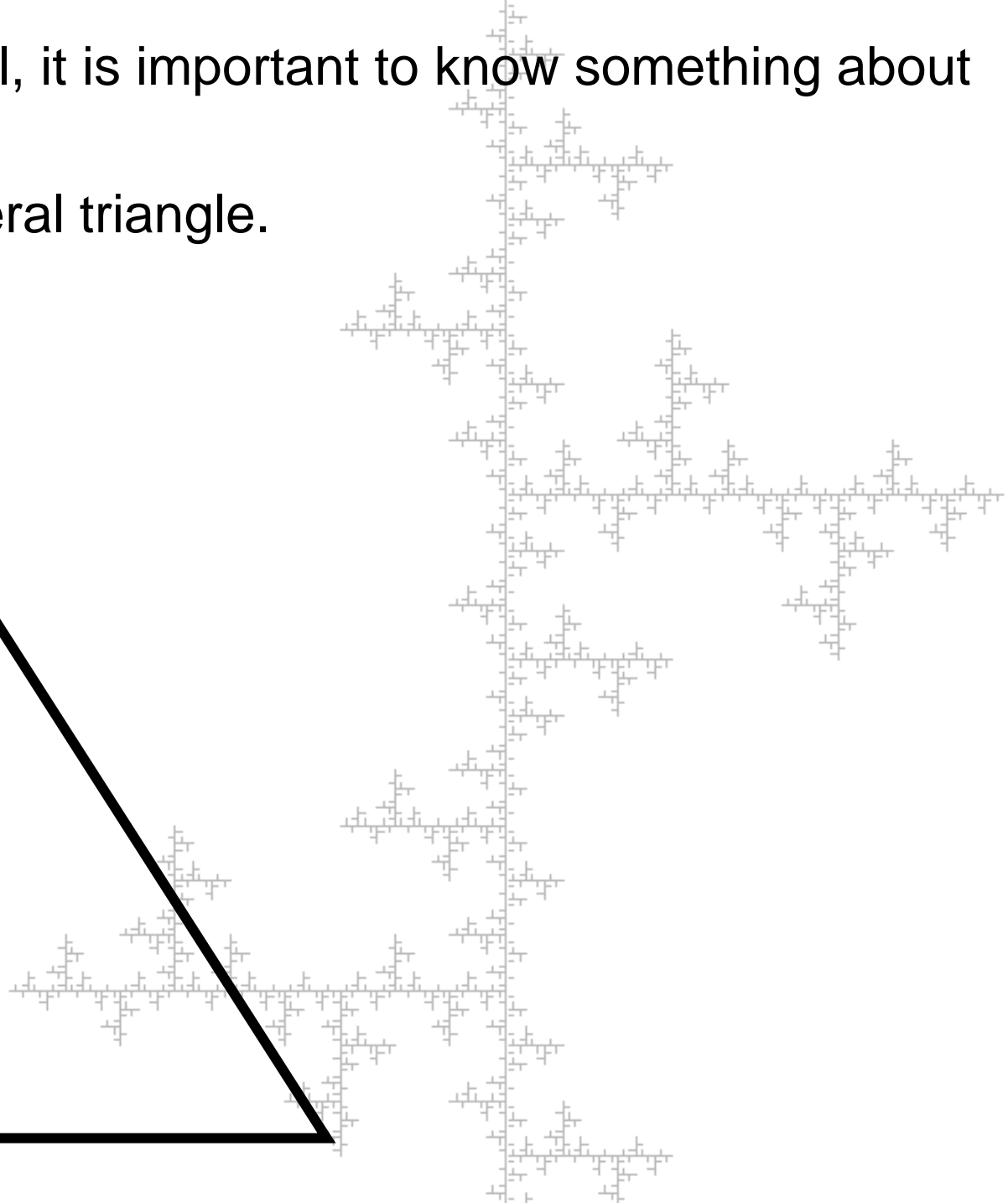
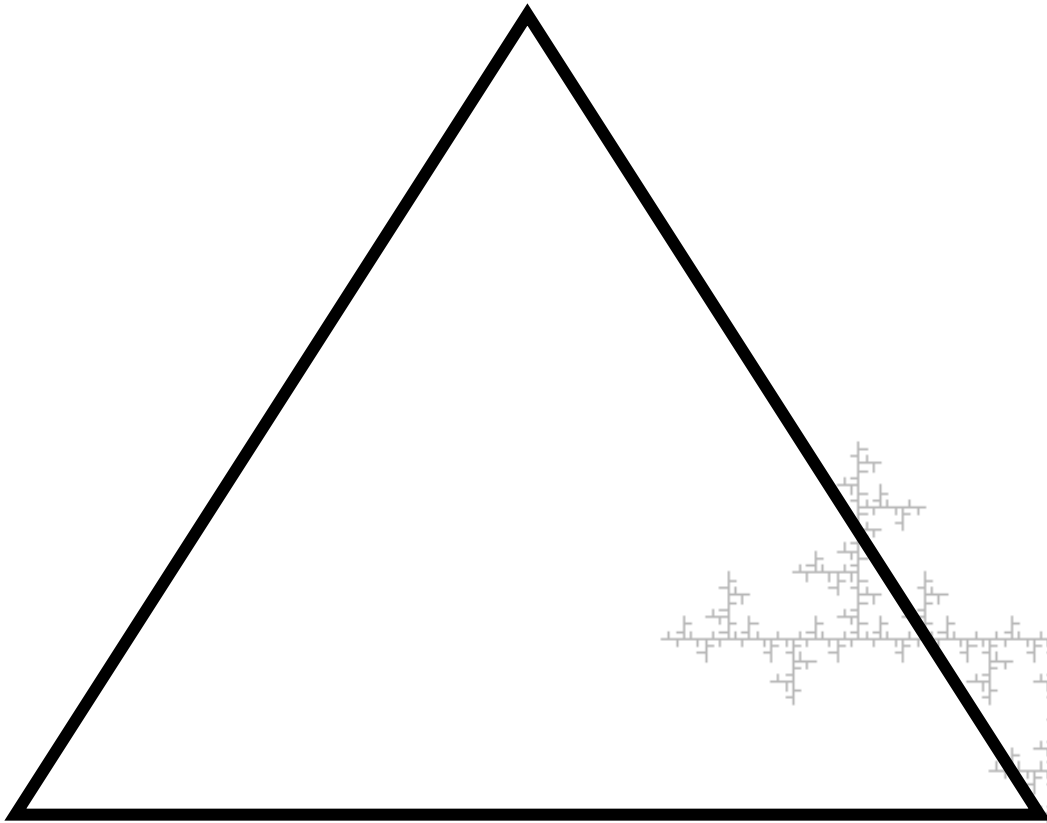


Image created using MathCad by Byrge Birkeland of Agder University College, Kristiansand, Norway

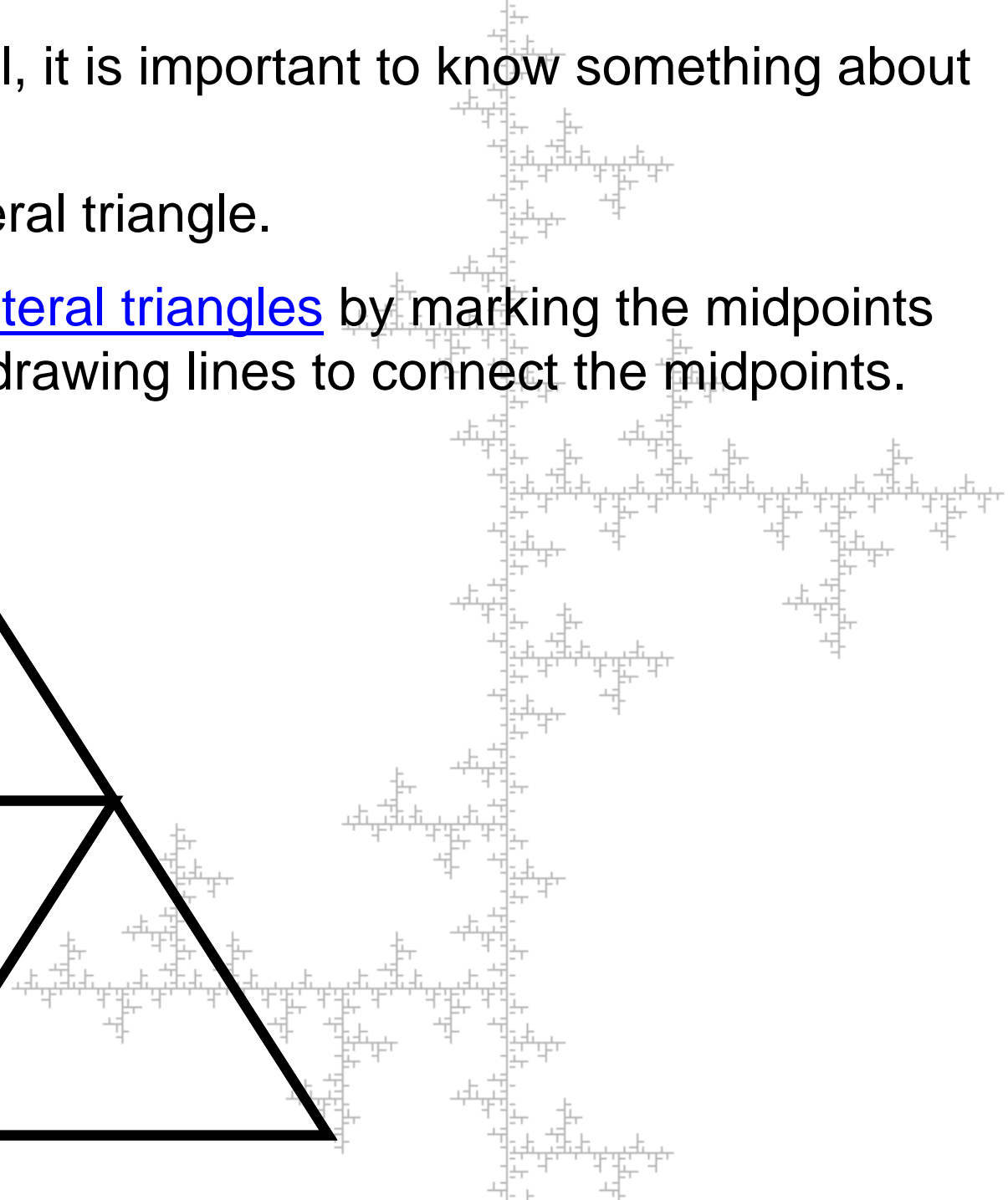
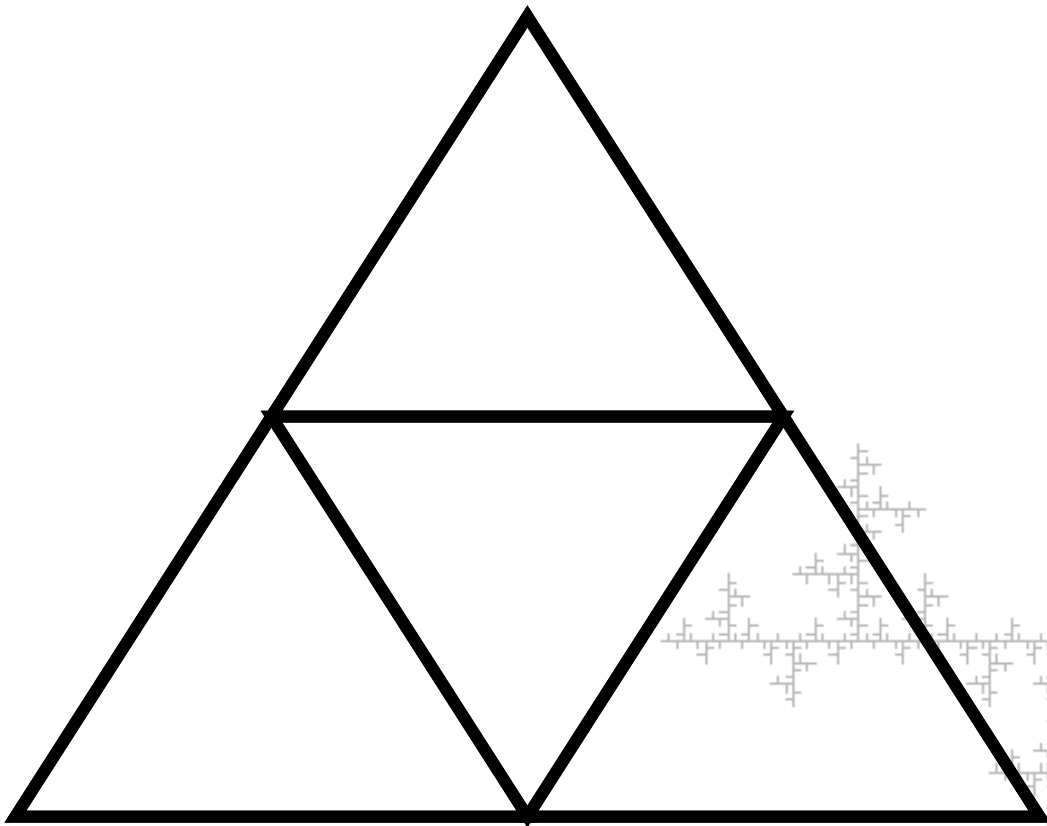
To consider this fractal, it is important to know something about a [tetrahedron](#).

- Start with an equilateral triangle.



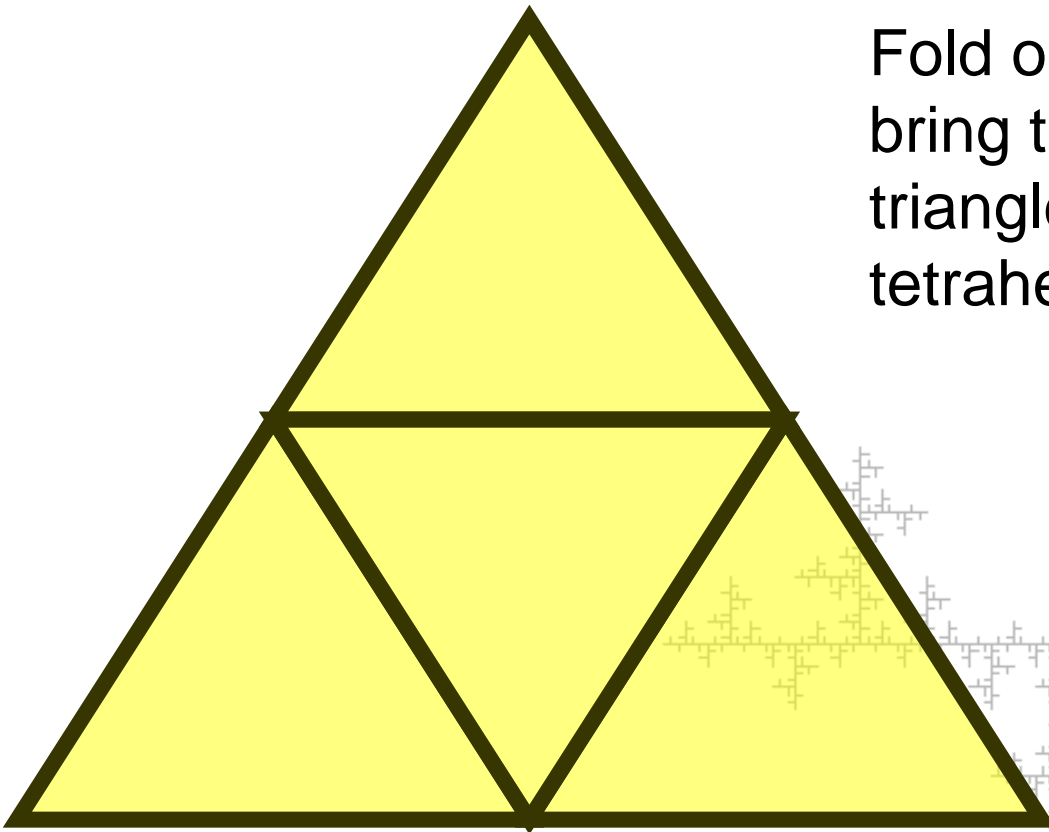
To consider this fractal, it is important to know something about a [tetrahedron](#).

- Start with an equilateral triangle.
- Divide it into 4 [equilateral triangles](#) by marking the midpoints of all three sides and drawing lines to connect the midpoints.

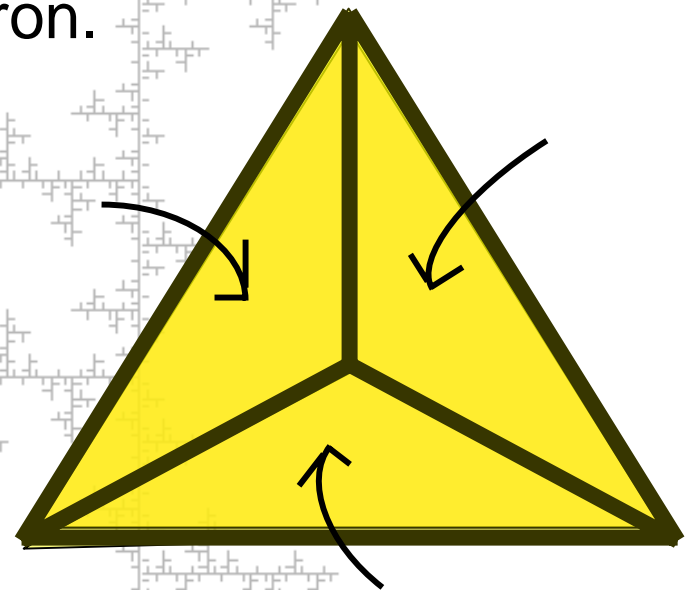


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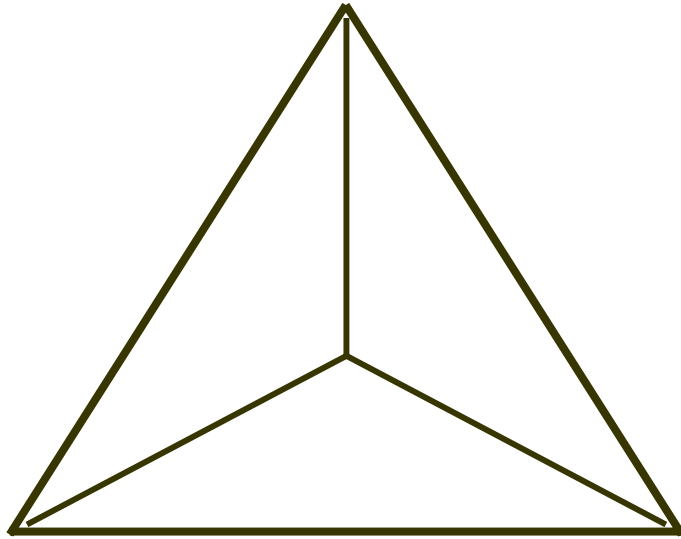
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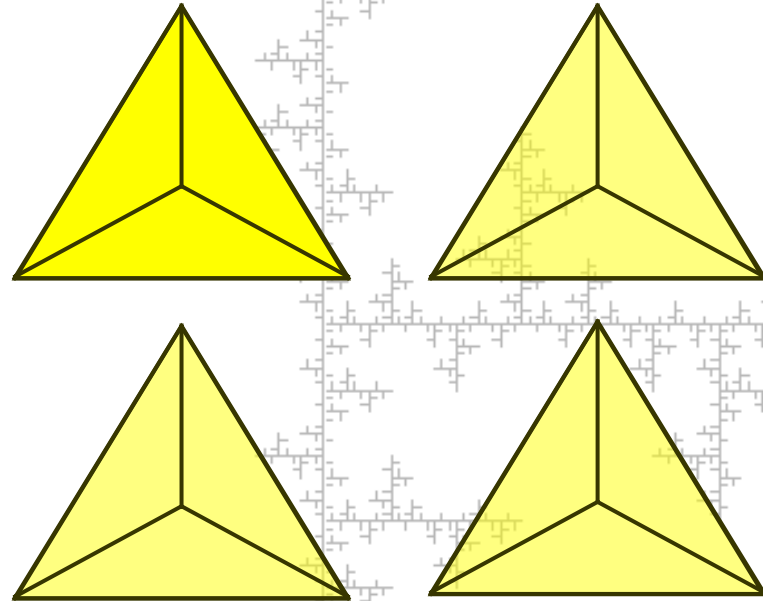
Fold on the [midpoint](#) lines and bring the tips of the equilateral triangle together to make a tetrahedron.



To build a stage-1:



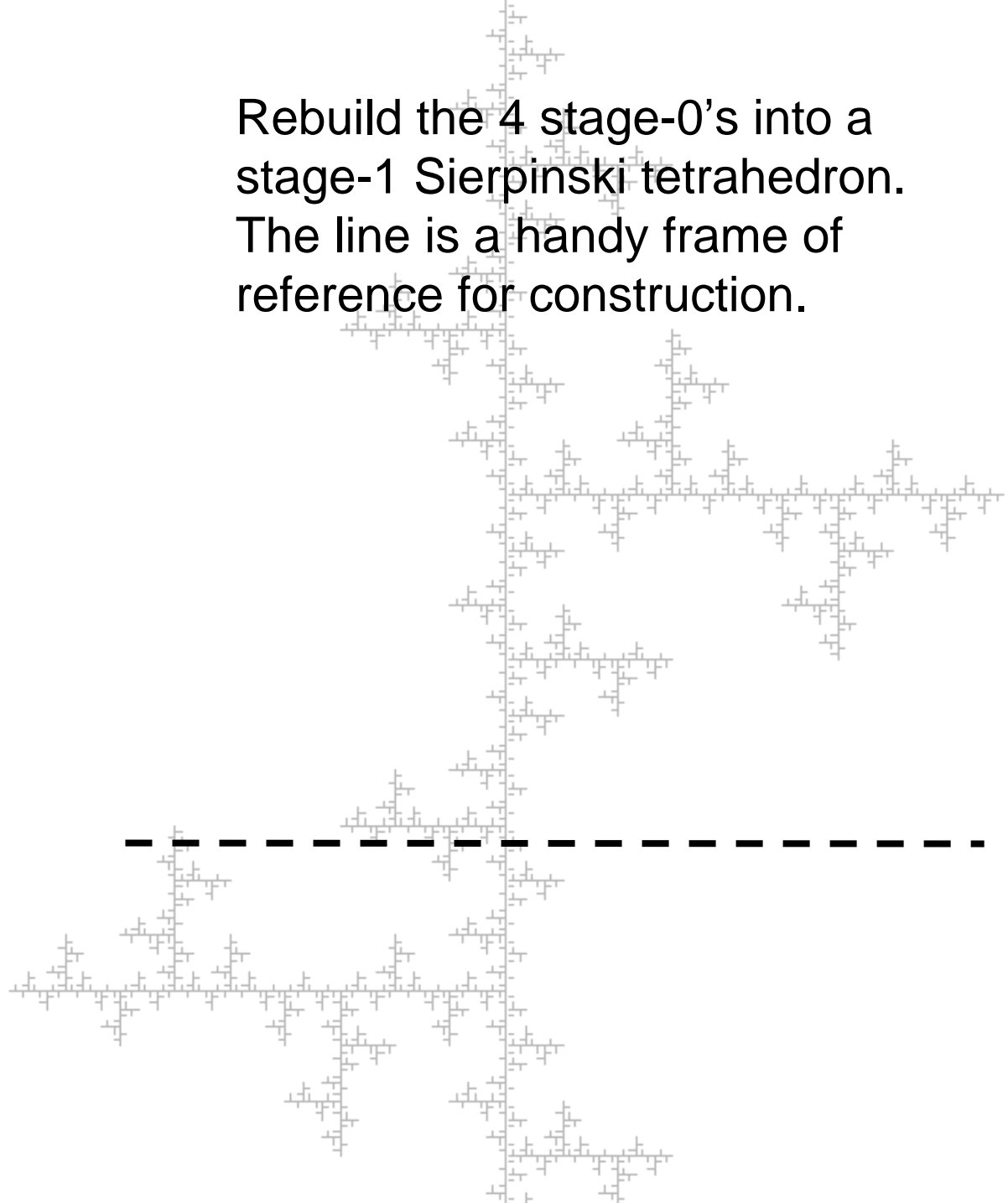
Start with a [regular](#) tetrahedron. It is called the stage-0 in the Sierpinski tetrahedron fractal family.



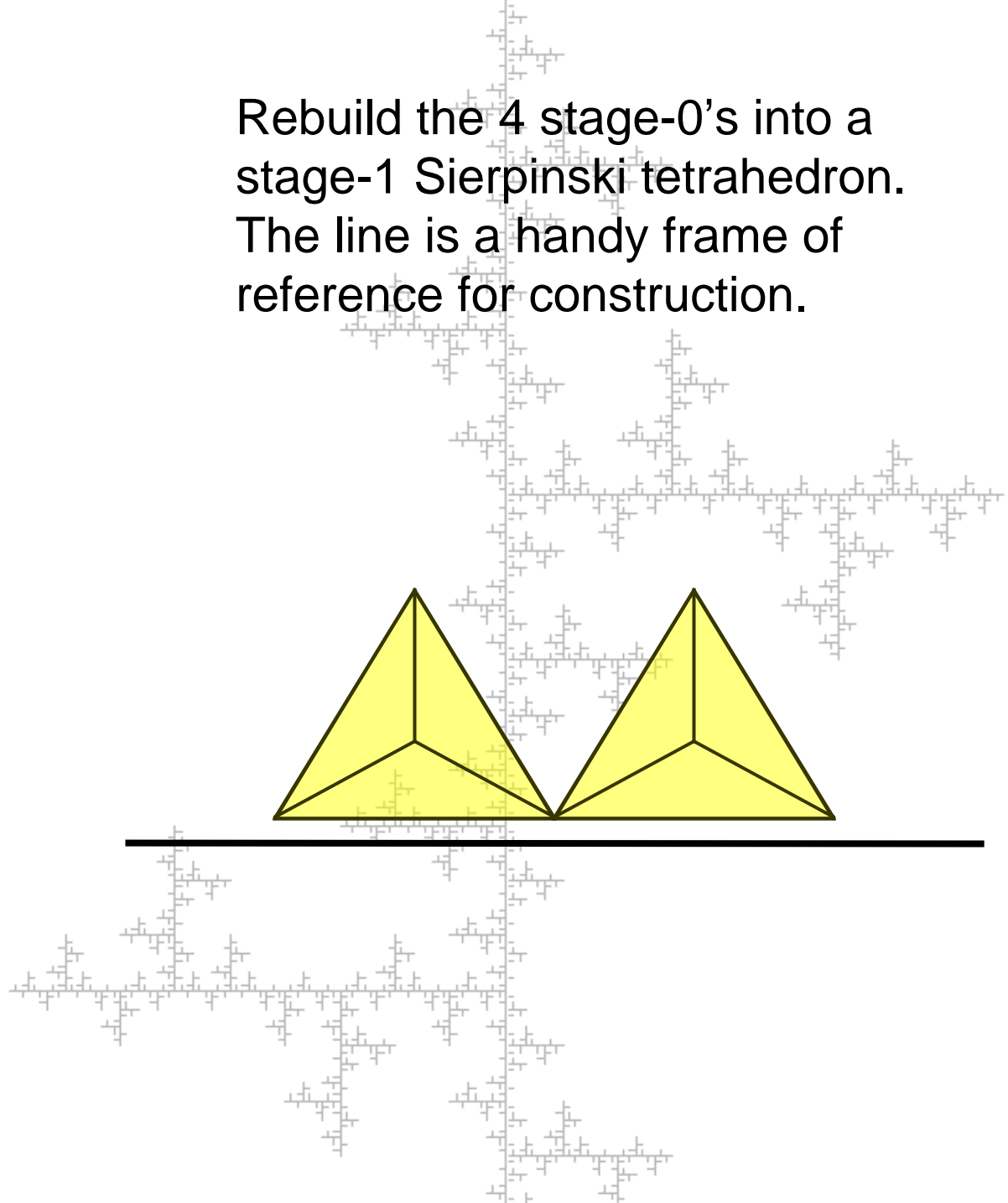
Reduce it by a [factor](#) of $1/2$

Replicate (4 are needed). The tetrahedra are kept transparent on this slide to reinforce that these are tetrahedra and not triangles.

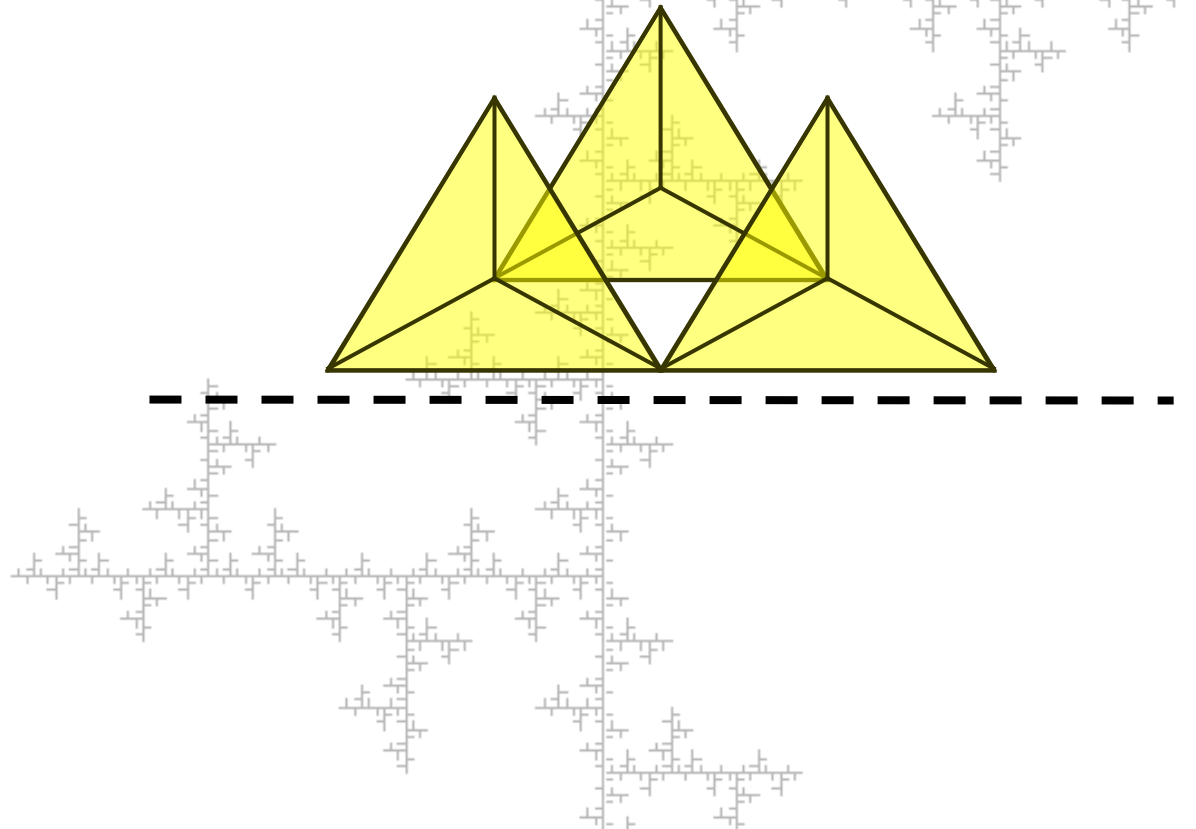
Rebuild the 4 stage-0's into a stage-1 Sierpinski tetrahedron. The line is a handy frame of reference for construction.



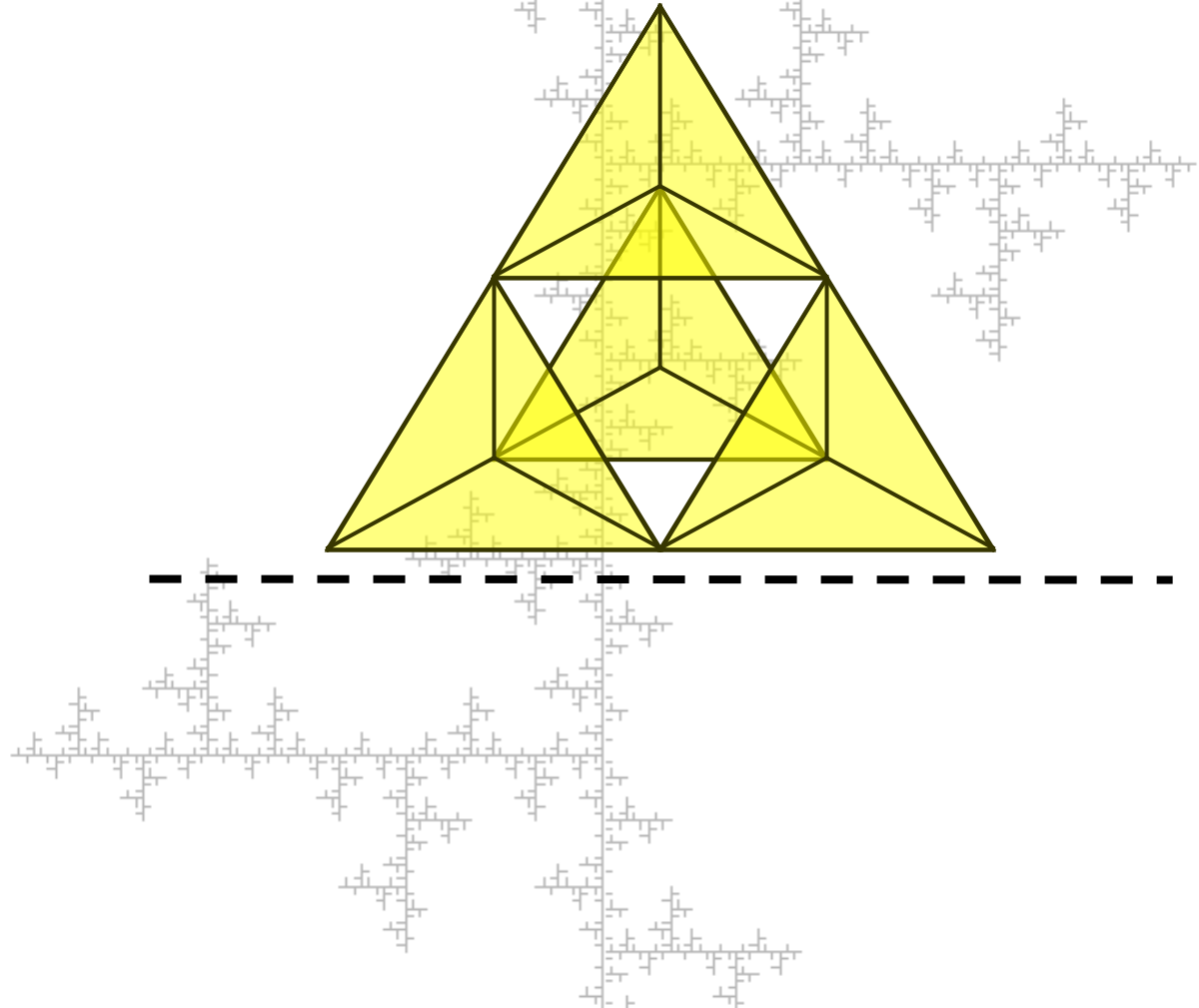
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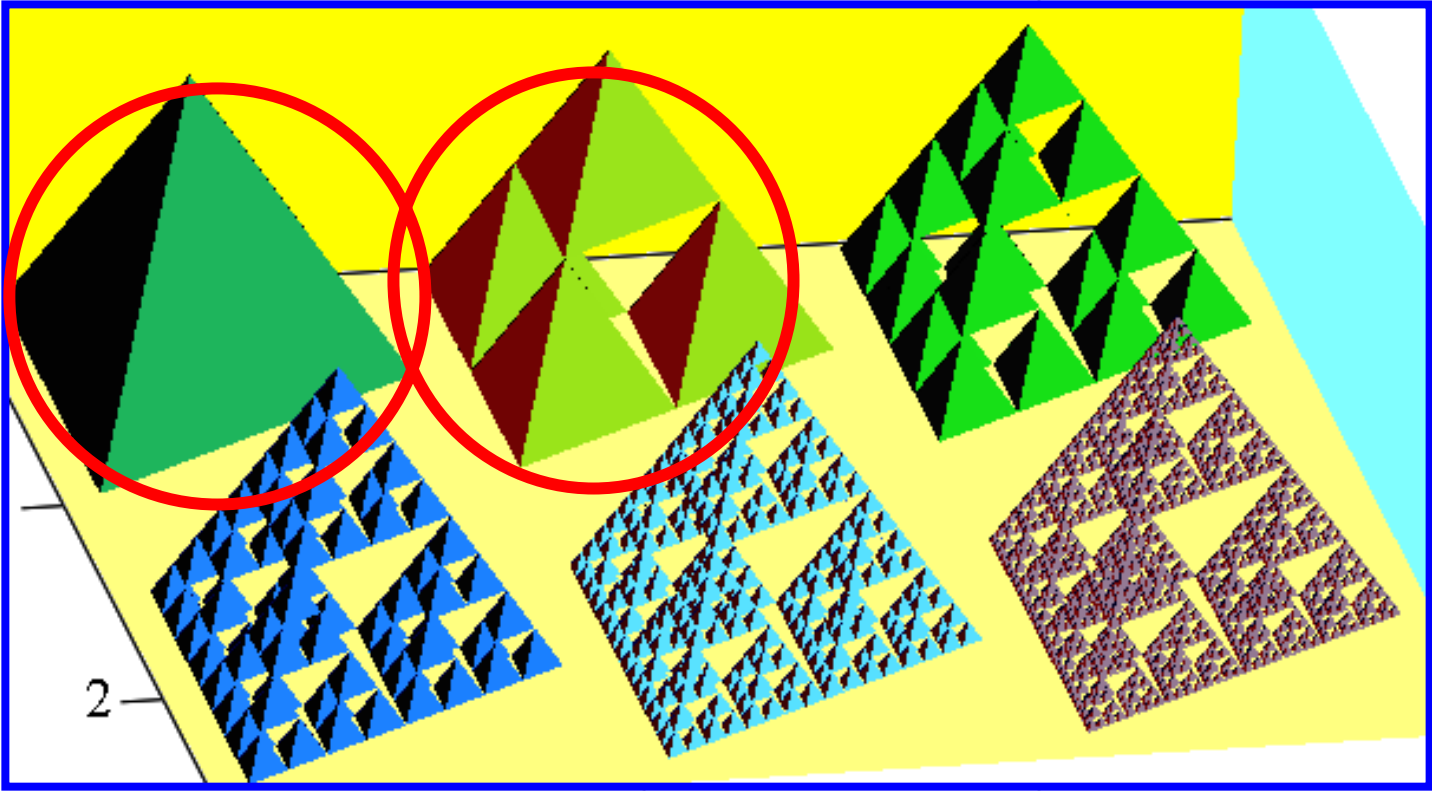
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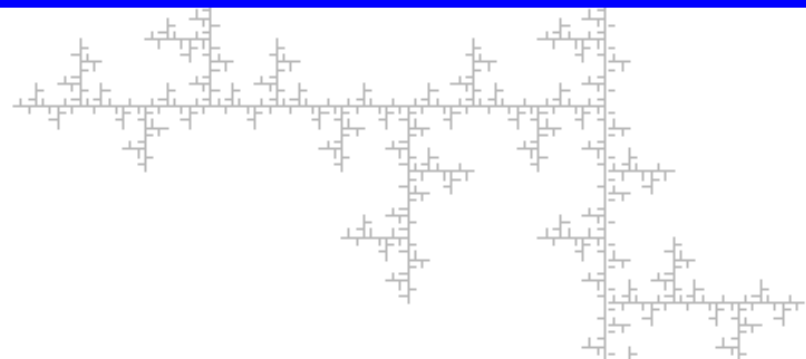
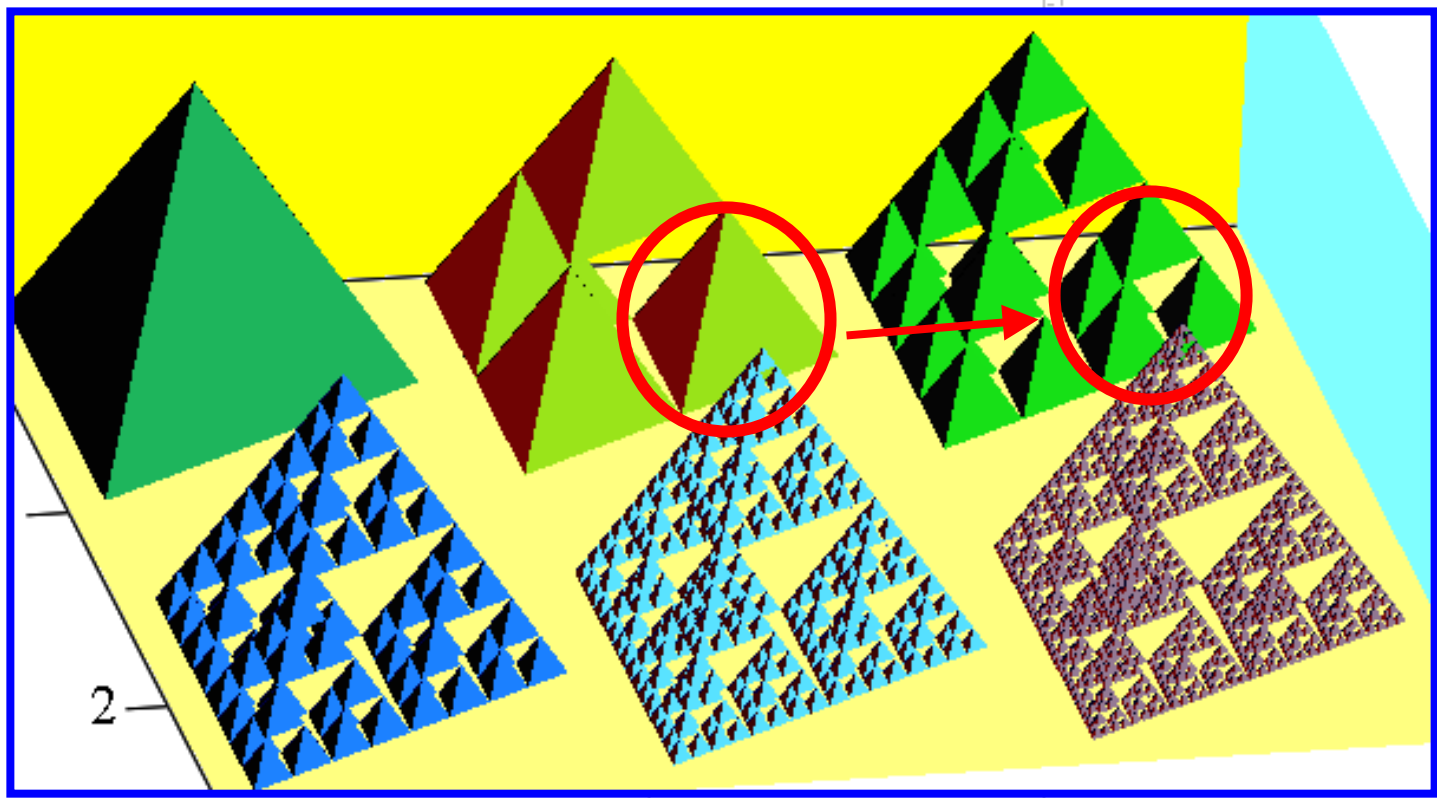


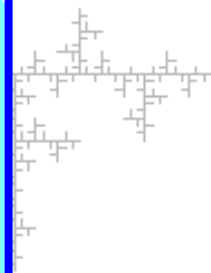
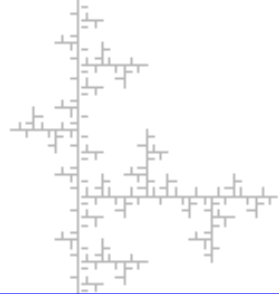
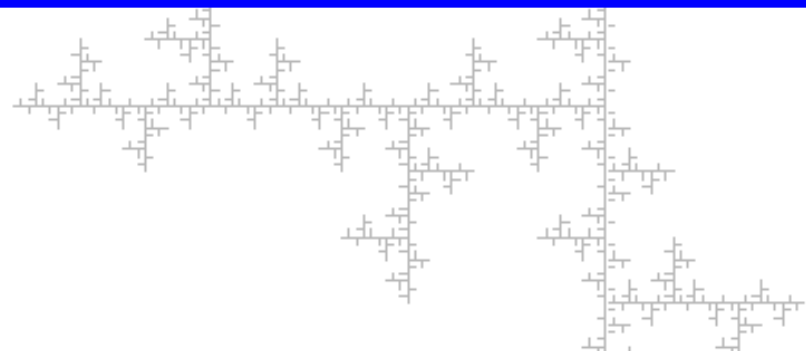
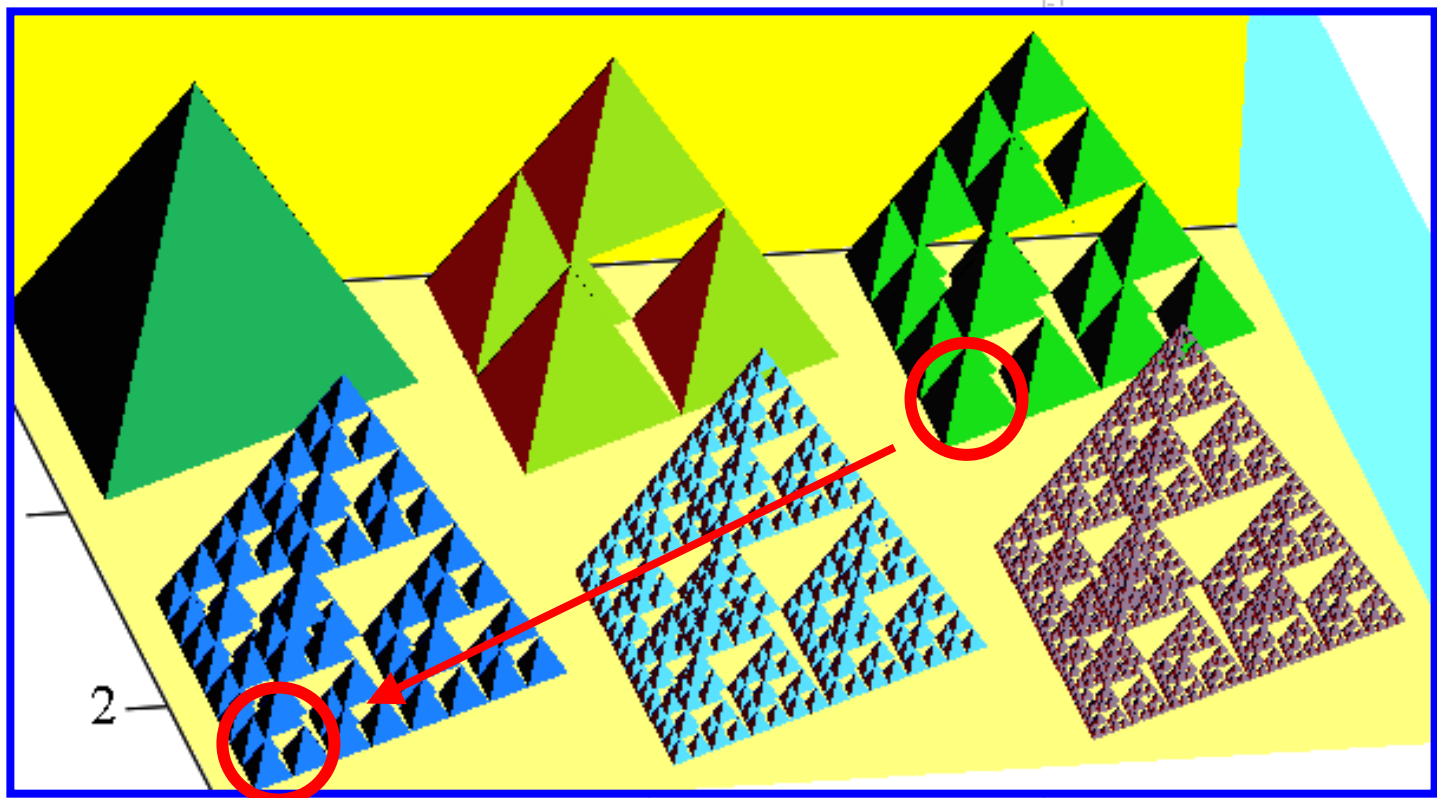
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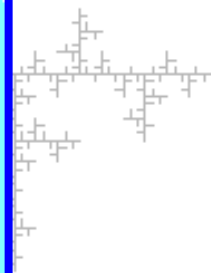
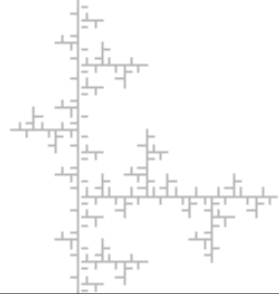
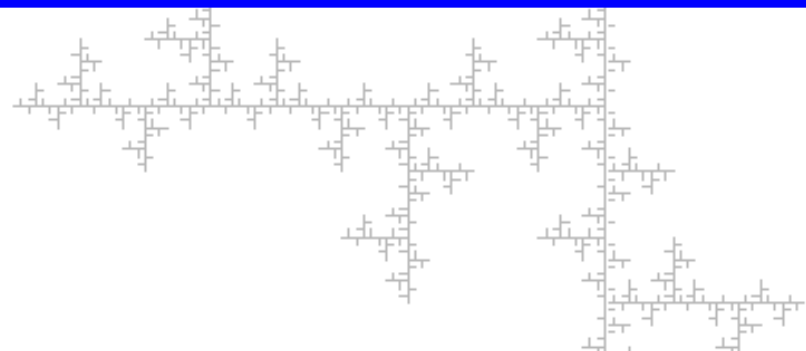
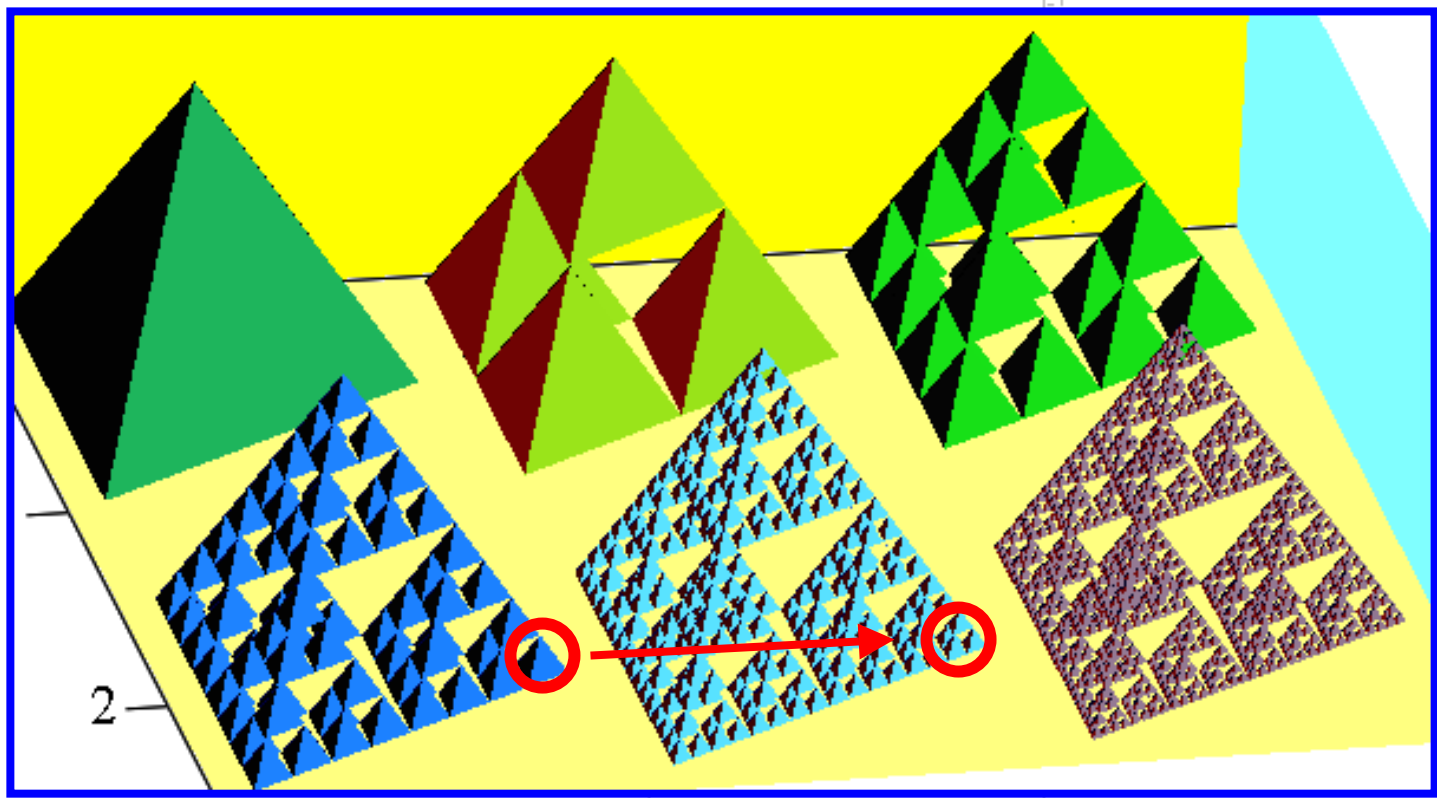


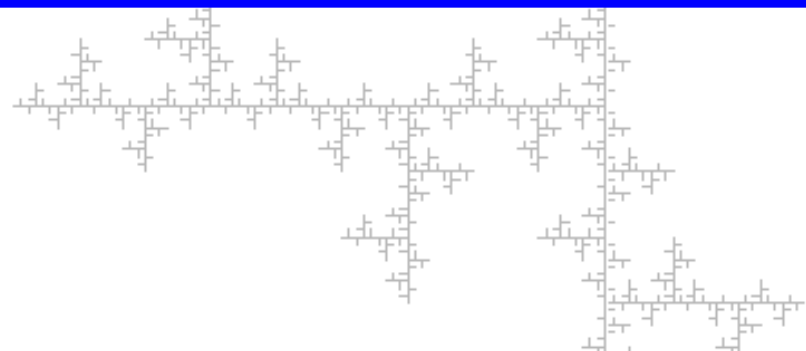
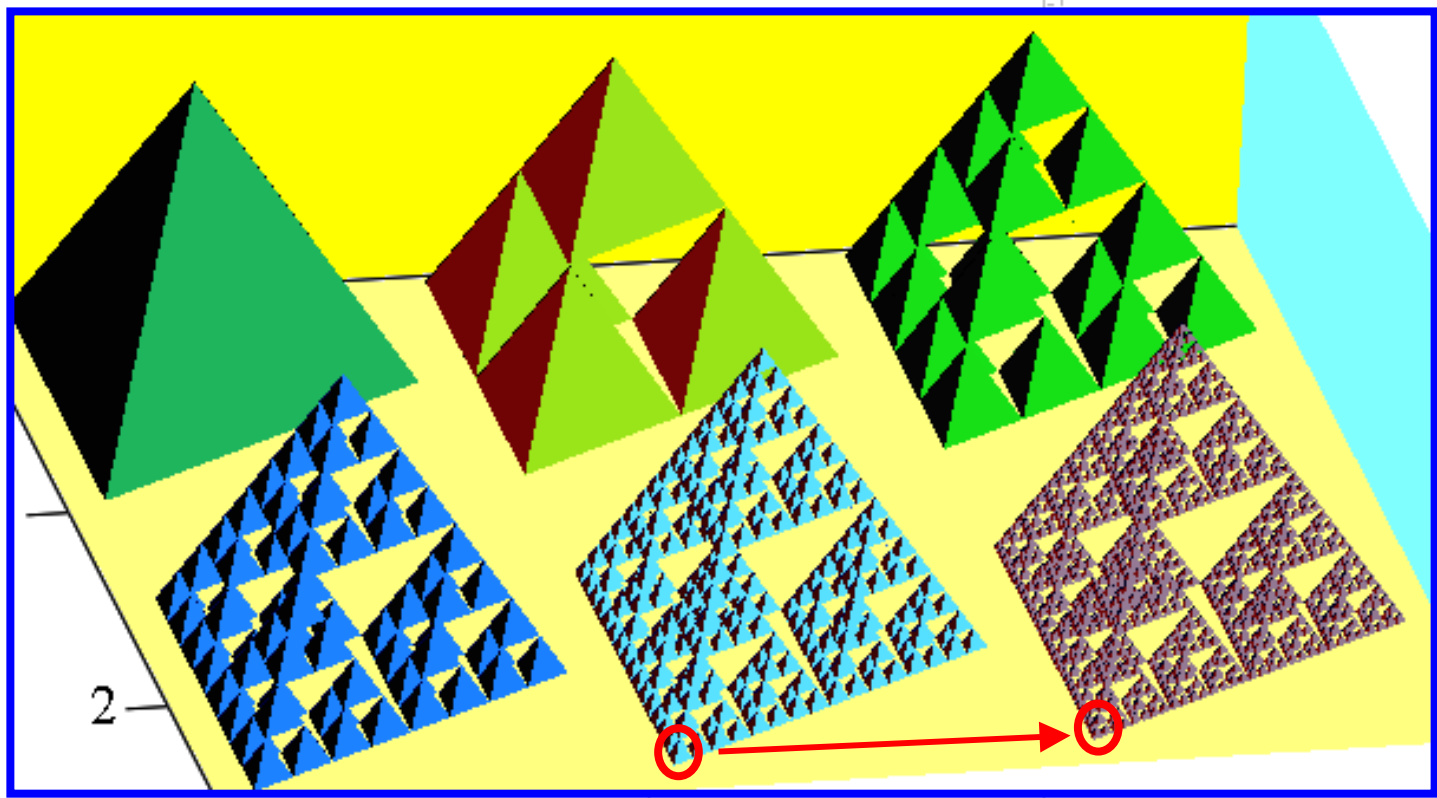
Revisiting the earlier image, notice that each tetrahedron is replaced by 4 tetrahedra in the next stage.

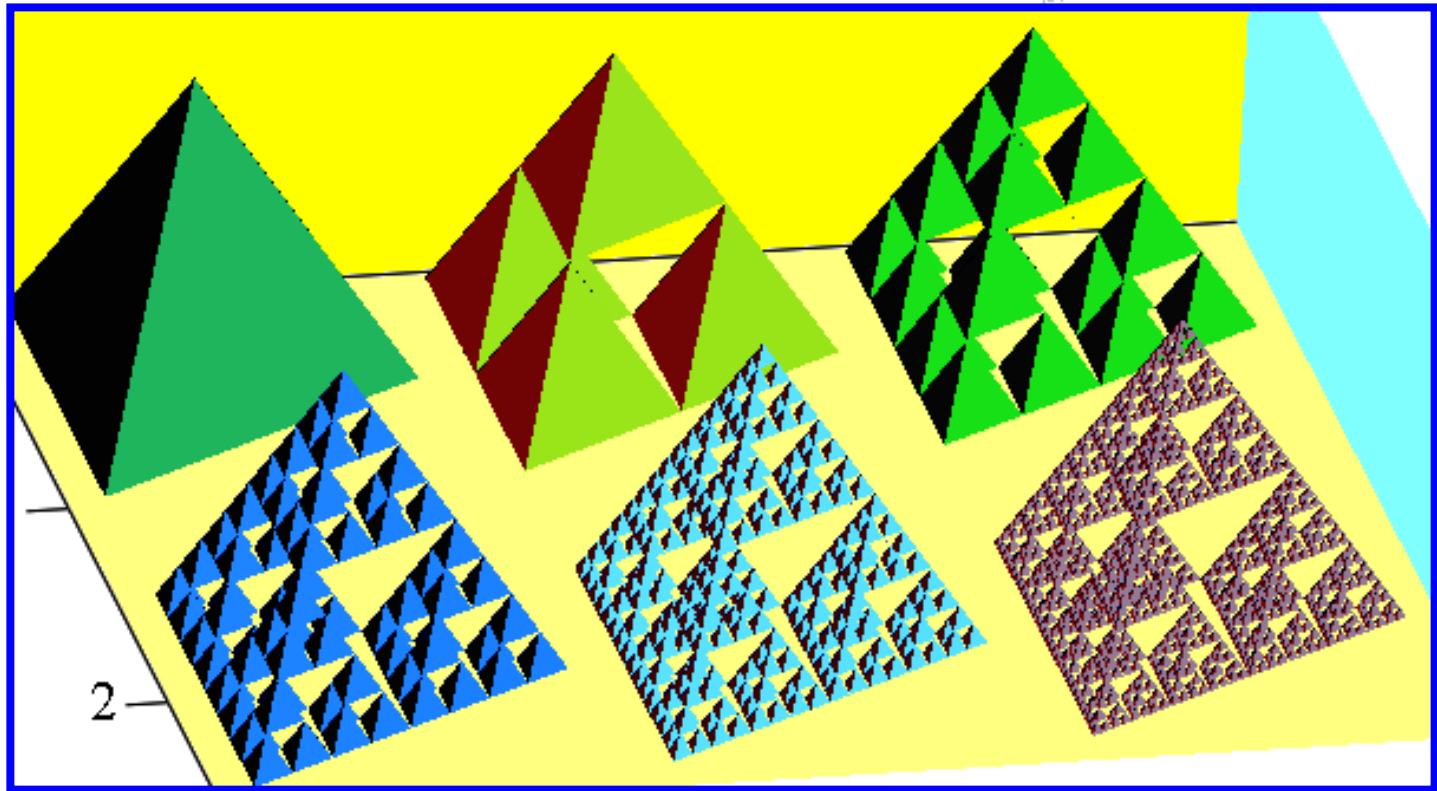












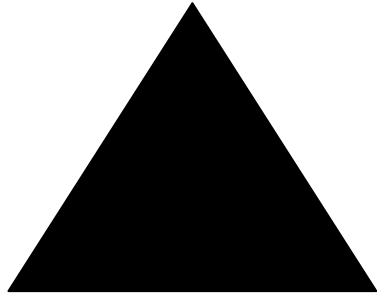
Determine the stage by counting the number of **sizes** of openings, the stage-1 has one size of opening, the stage-2 two **sizes** of openings, etc...

What is happening to all that removed volume in Sierpinski's tetrahedron? You can view it on my [Sierpinski Tetrahedron and its Complement](#) page.

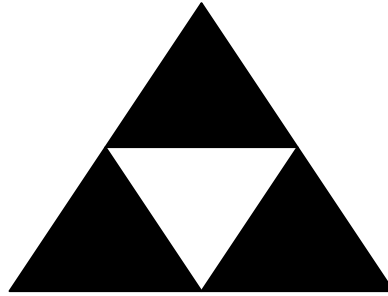
This and more can be seen on on Paul Bourke's [Platonic Solids Fractals and their Complements](#) page.

The Sierpinski tetrahedron is a volume analog of
the Sierpinski triangle:

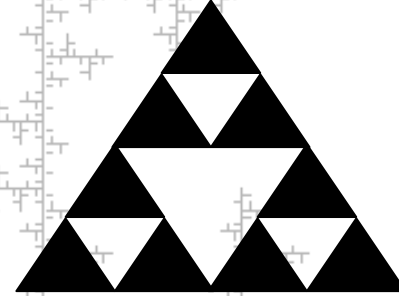
The Sierpinski Triangle: grows in Powers of 3



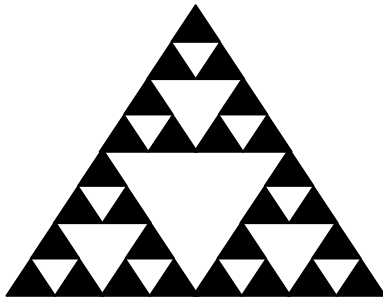
Notice how each triangle *becomes three triangles* in the next stage.



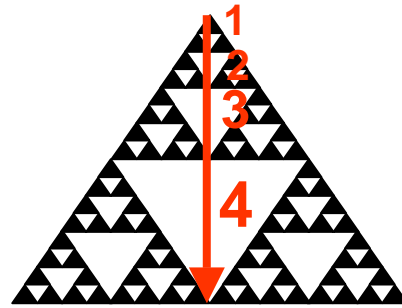
Reduce by $\frac{1}{2}$ Replicate & Rebuild



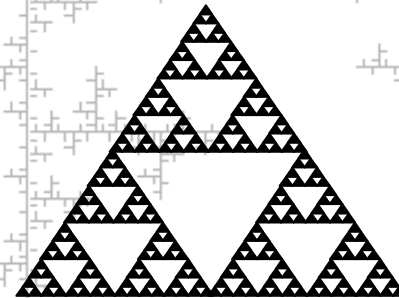
Reduce by $\frac{1}{2}$ again Replicate & Rebuild



With this fractal, it is surface area instead of volume that is decreasing at each stage.



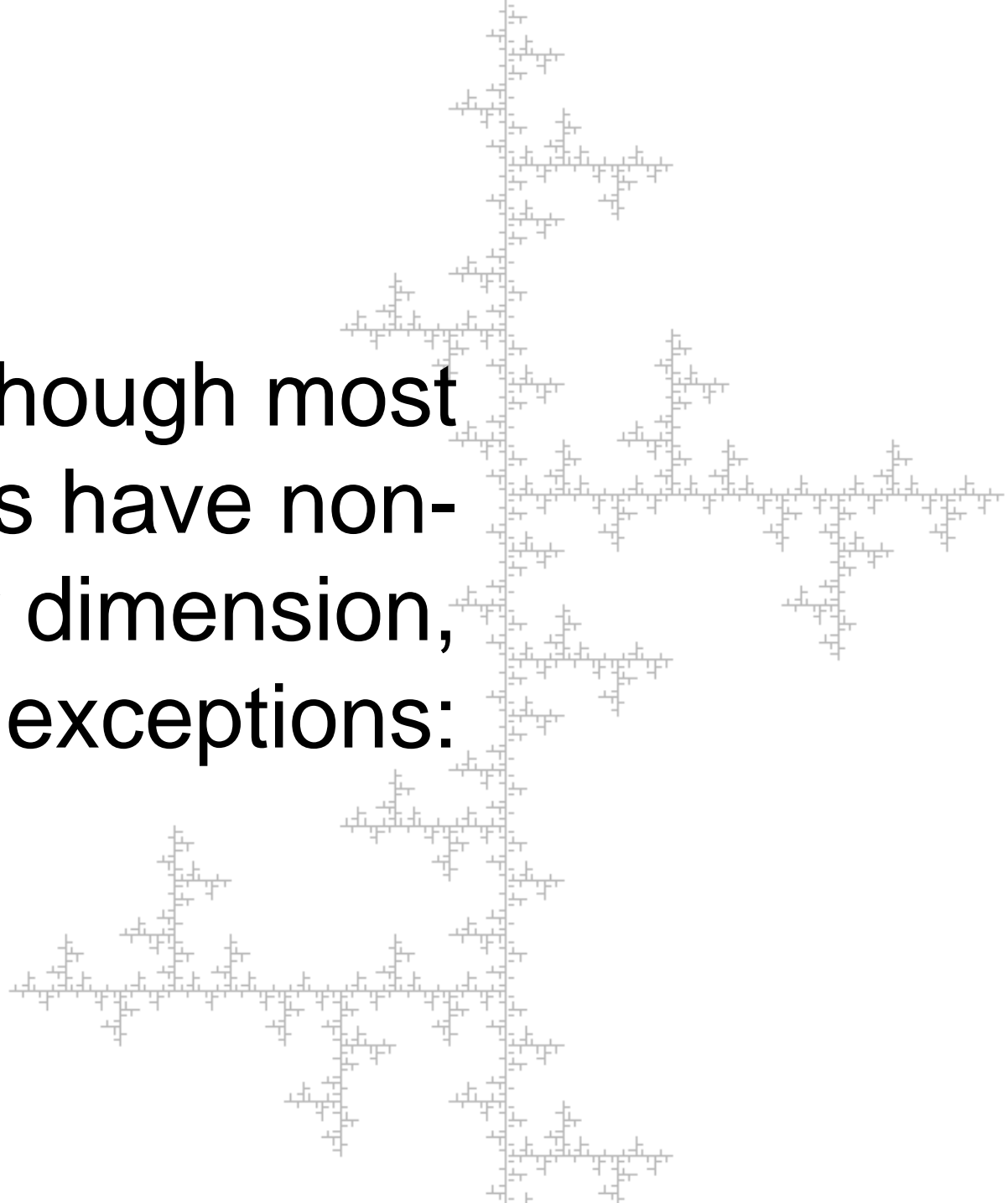
The stage can be determined by the number of different *sizes* of openings.



The face of a Sierpinski tetrahedron is a same-stage Sierpinski triangle.

Geometric fractals are typically filling or emptying something, whether it is length, surface area, or volume. The key points are that dimension is: 1) changing, and 2) generally fractional.

Even though most
fractals have non-
integer dimension,
there are exceptions:



For exactly self-similar shapes made of N copies, each scaled by a factor of r , the dimension is

$$\text{Log}(N)/\text{Log}(1/r)$$

The [Sierpinski tetrahedron](#) is made of $N = 4$ copies, each scaled by a factor of $r = 1/2$, so its dimension is

$$\text{Log}(4)/\text{Log}(2) = 2$$

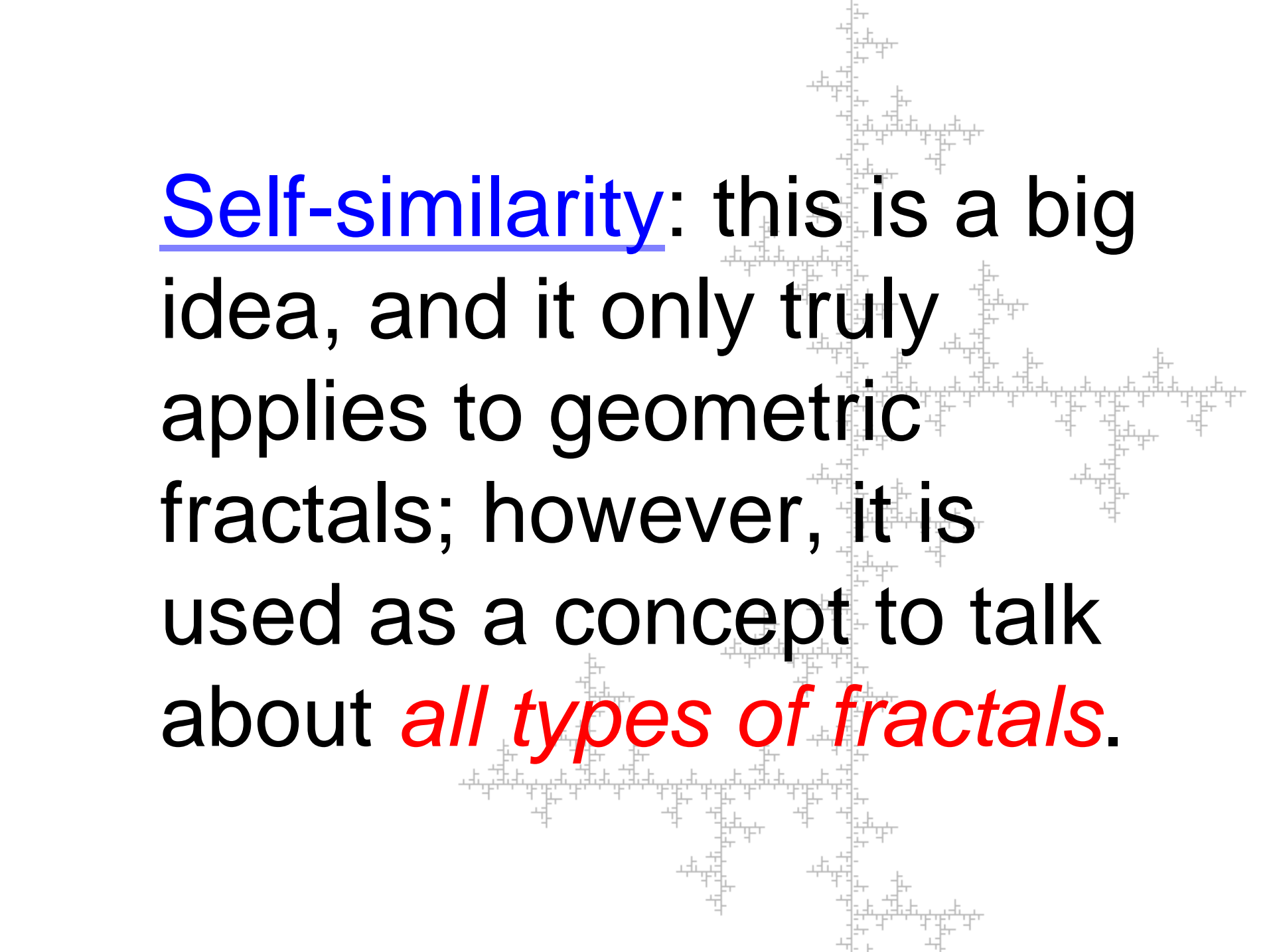
So the Sierpinski tetrahedron is a shape that is manifestly fractal, but has integer dimension!

Contrast this with the **Sierpinski triangle**, made of $N = 3$ copies, each scaled by a factor of $r = \frac{1}{2}$. Its dimension is

$$\text{Log}(3)/\text{Log}(2) \approx 1.58496\dots$$

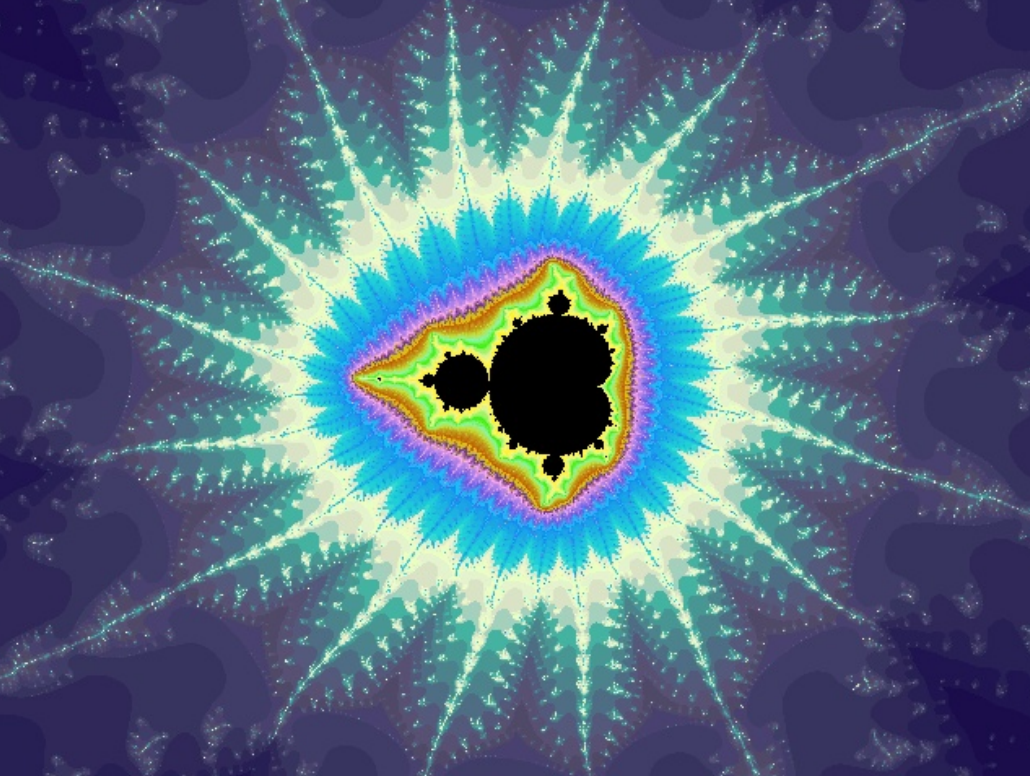
The **Sierpinski triangle** has fractional dimension, more typical of fractals.

The exact answer above is $\text{Log}(3)/\text{Log}(2)$. The approximate answer is the decimal approximation 1.58496... Rule of thumb: keep answers in exact form unless a decimal approximation is requested, and when requested, wait until the very end to convert to a decimal to avoid rounding error.



Self-similarity: this is a big idea, and it only truly applies to geometric fractals; however, it is used as a concept to talk about *all types of fractals*.

Something is self-similar when every little part looks exactly like the whole. The only place this can really happen is in a perfect (Ideal) system at infinity; however, in order to speak about fractals generally, one must embrace the *concept* of self-similarity in a broad way.



(Everything on this slide links to relevant websites; url's are included since links aren't coming thru the conversion to PDF.)

Chaos

<http://classes.yale.edu/fractals/Chaos/ChaosIntro/ChaosIntro.html>

Multifractals

<http://classes.yale.edu/fractals/MultiFractals/welcome.html>

Random Fractals

<http://classes.yale.edu/fractals/RandFrac/welcome.html>

Complex Fractals

<http://www.geom.uiuc.edu/~zietlow/defp1.html>

Mandelbrot discusses fractals

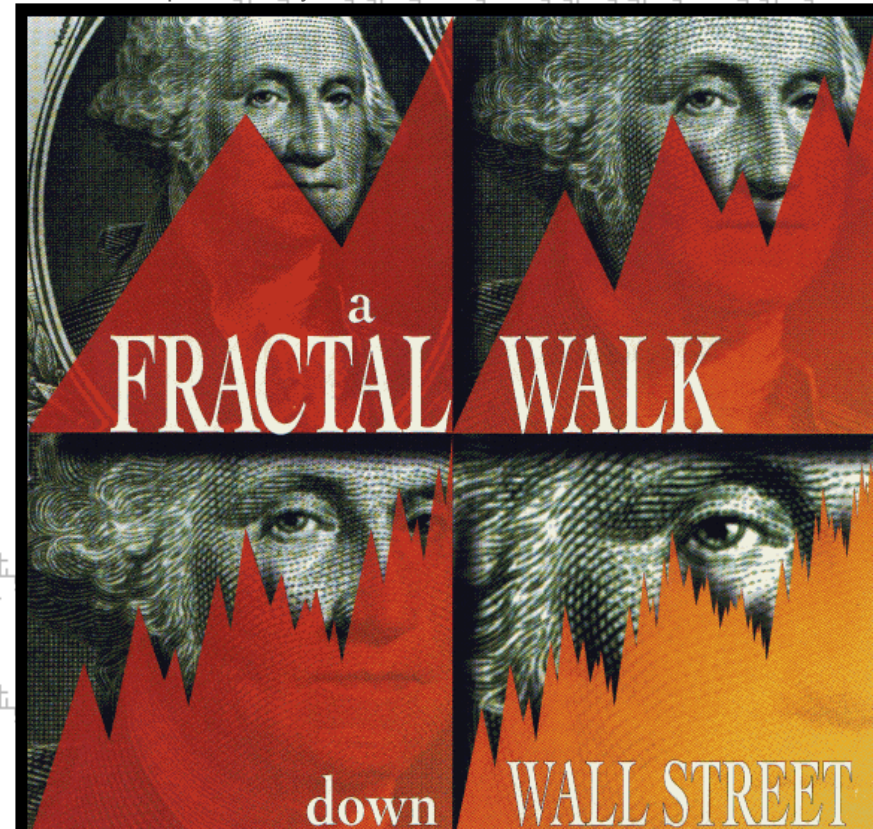
<http://www.yale.edu/opa/v31.n20/story6.html>

Mandelbrot Set

<http://www.ddewey.net/mandelbrot/noad.html>

Julia Sets

<http://www.ibiblio.org/e-notes/MSet/Period.htm>



Frames of Reference

Is there anything in this image to indicate the size of the clouds?

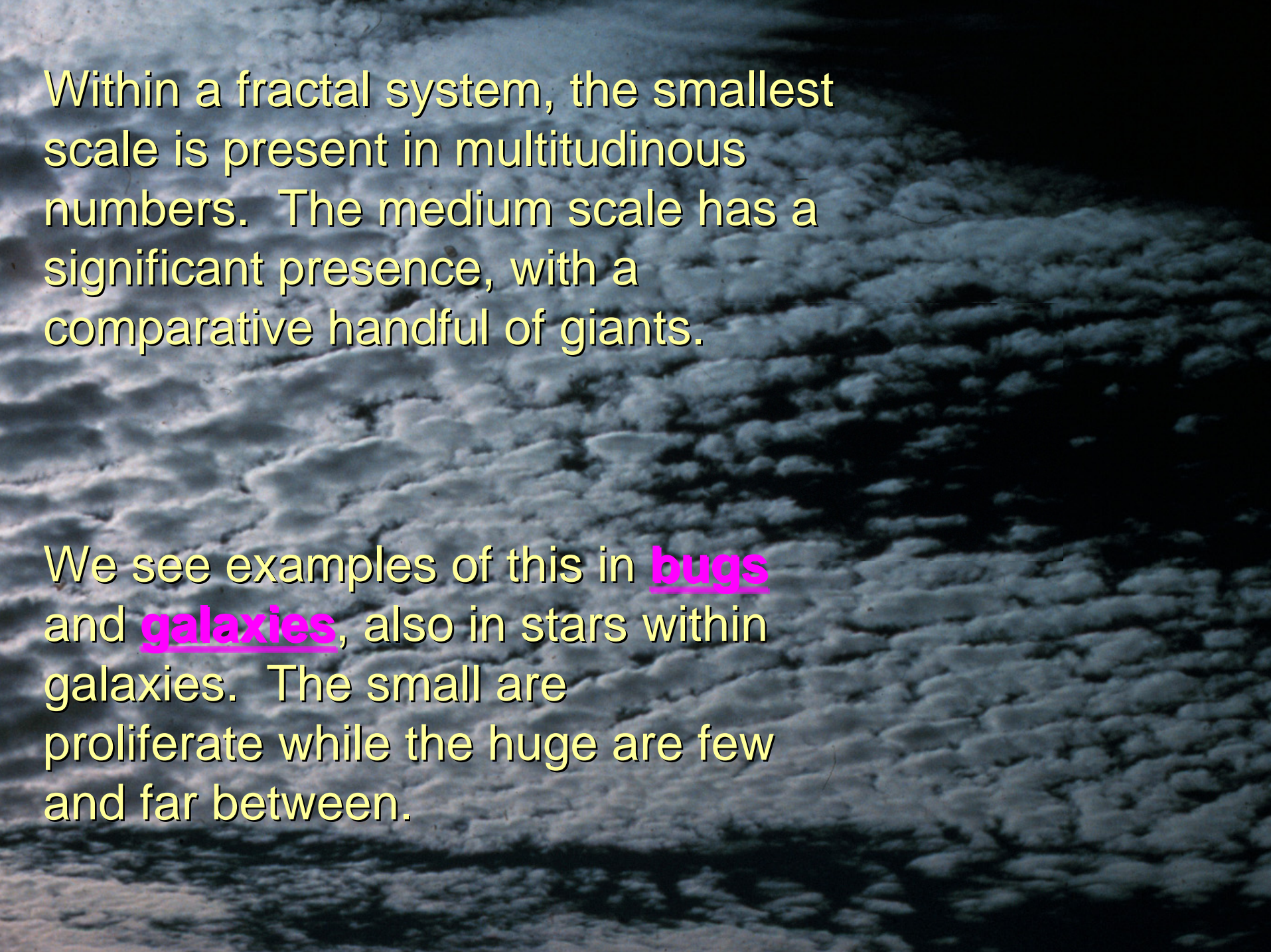
This image is scale-independent. It has no frame of reference to indicate the size of the clouds, such as an airplane, or the horizon.

Magnification symmetry requires a frame of reference to determine size because zooming in reveals approximately the same shape(s).



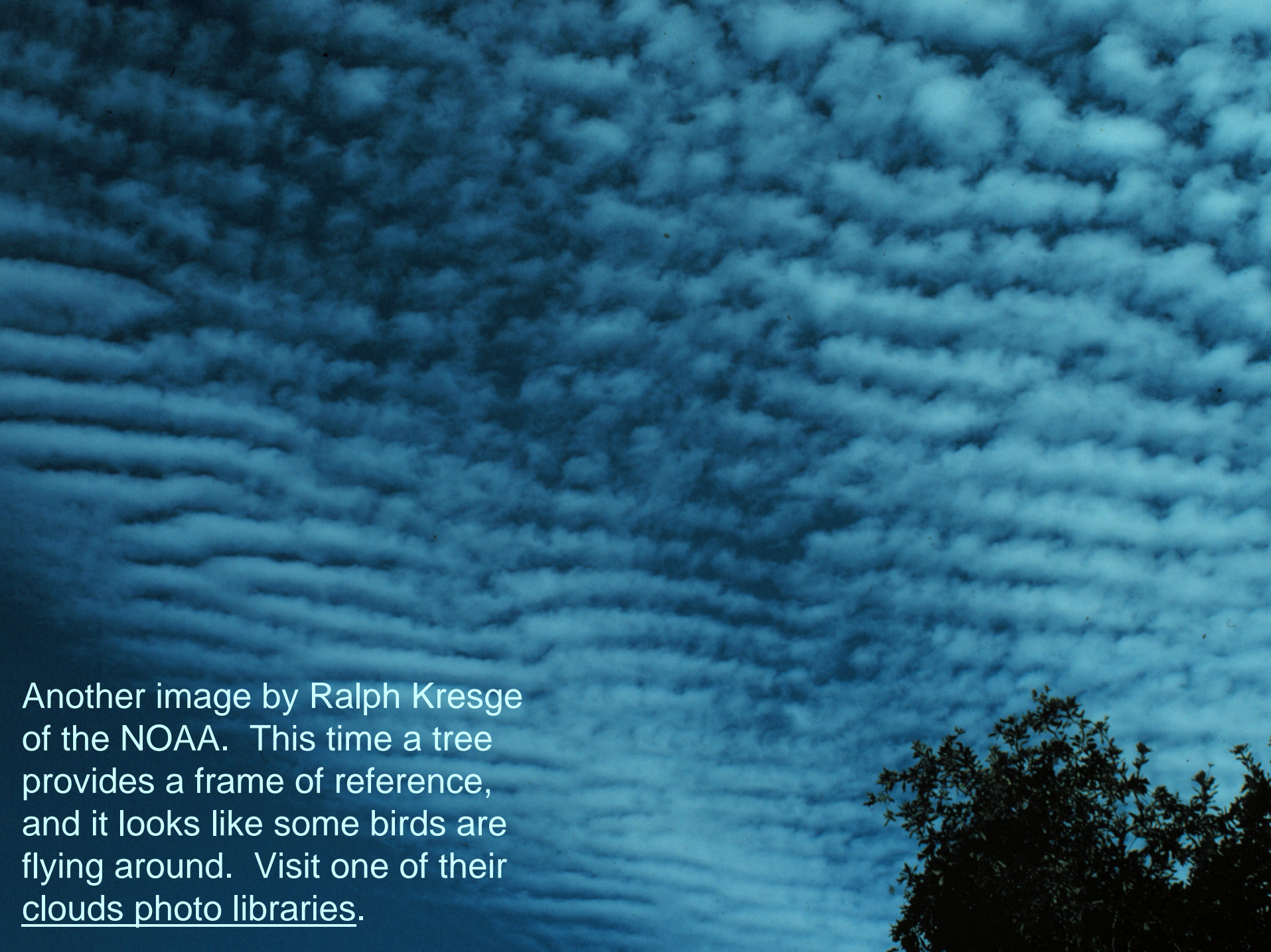
Taken by Ralph Kresge.
[National Weather Service](#)
[\(NOAA\) photo library](#)

Fractals are scale independent. Recall that small parts aggregate to dominate overall shape.



Within a fractal system, the smallest scale is present in multitudinous numbers. The medium scale has a significant presence, with a comparative handful of giants.

We see examples of this in bugs and galaxies, also in stars within galaxies. The small are proliferate while the huge are few and far between.



Another image by Ralph Kresge of the NOAA. This time a tree provides a frame of reference, and it looks like some birds are flying around. Visit one of their [clouds photo libraries](#).

Examine exponential growth in a geometric fractal: the Menger Sponge.

The Menger Sponge is part of a series of fractals, in that while it is Volumetric, it has Length and Area analogs. The Area analog, the Sierpinski Carpet (seen in image), is used by [Fractal Antenna Systems](#) as an antenna in cell phones. The number of scales allows for a wide range of receptions.

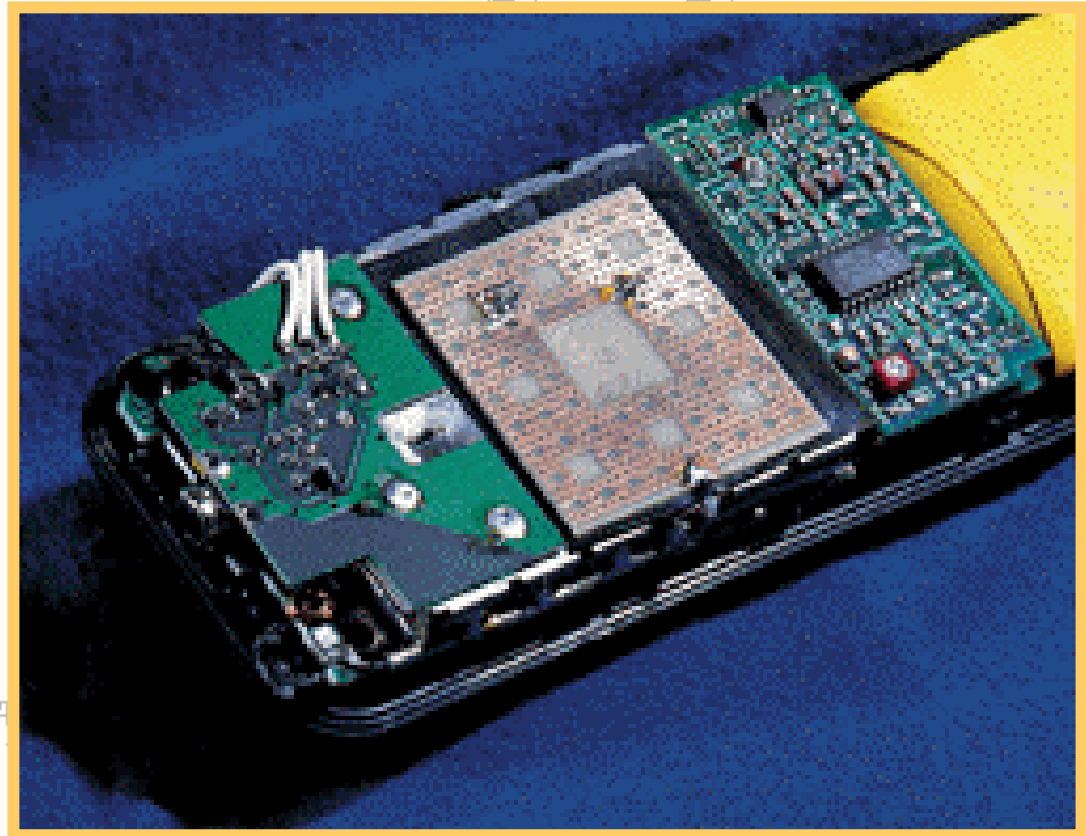
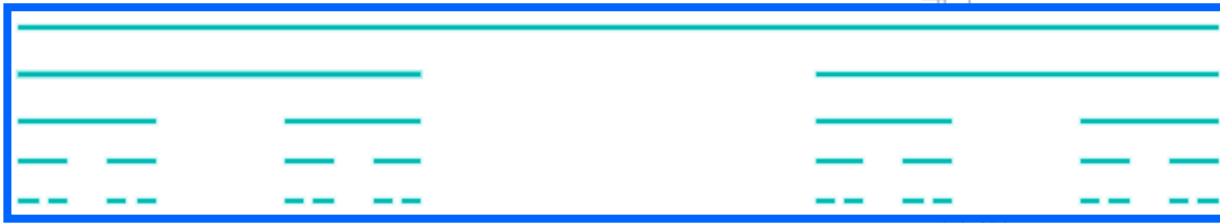
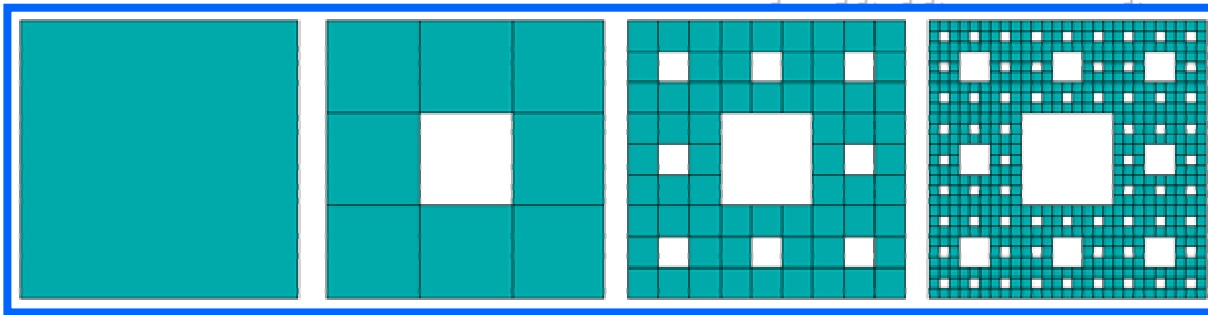


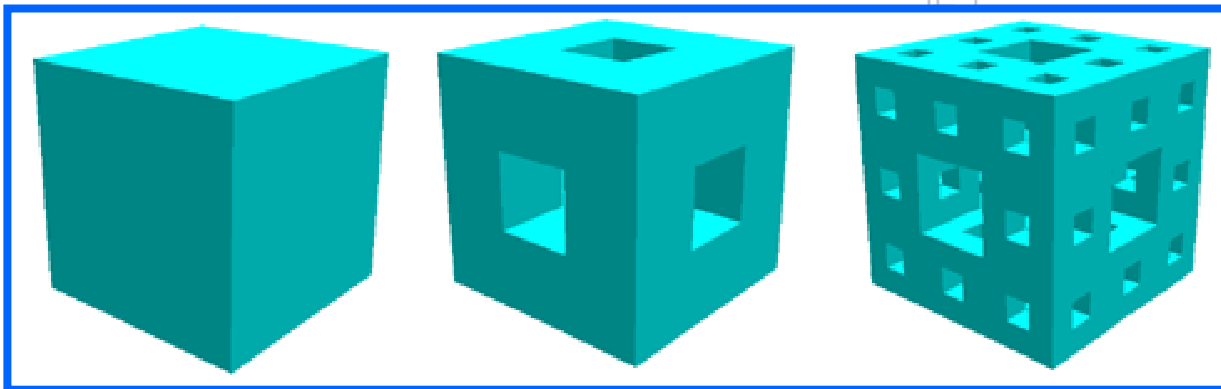
Image from Yale's [Fractal Antennas](#) page



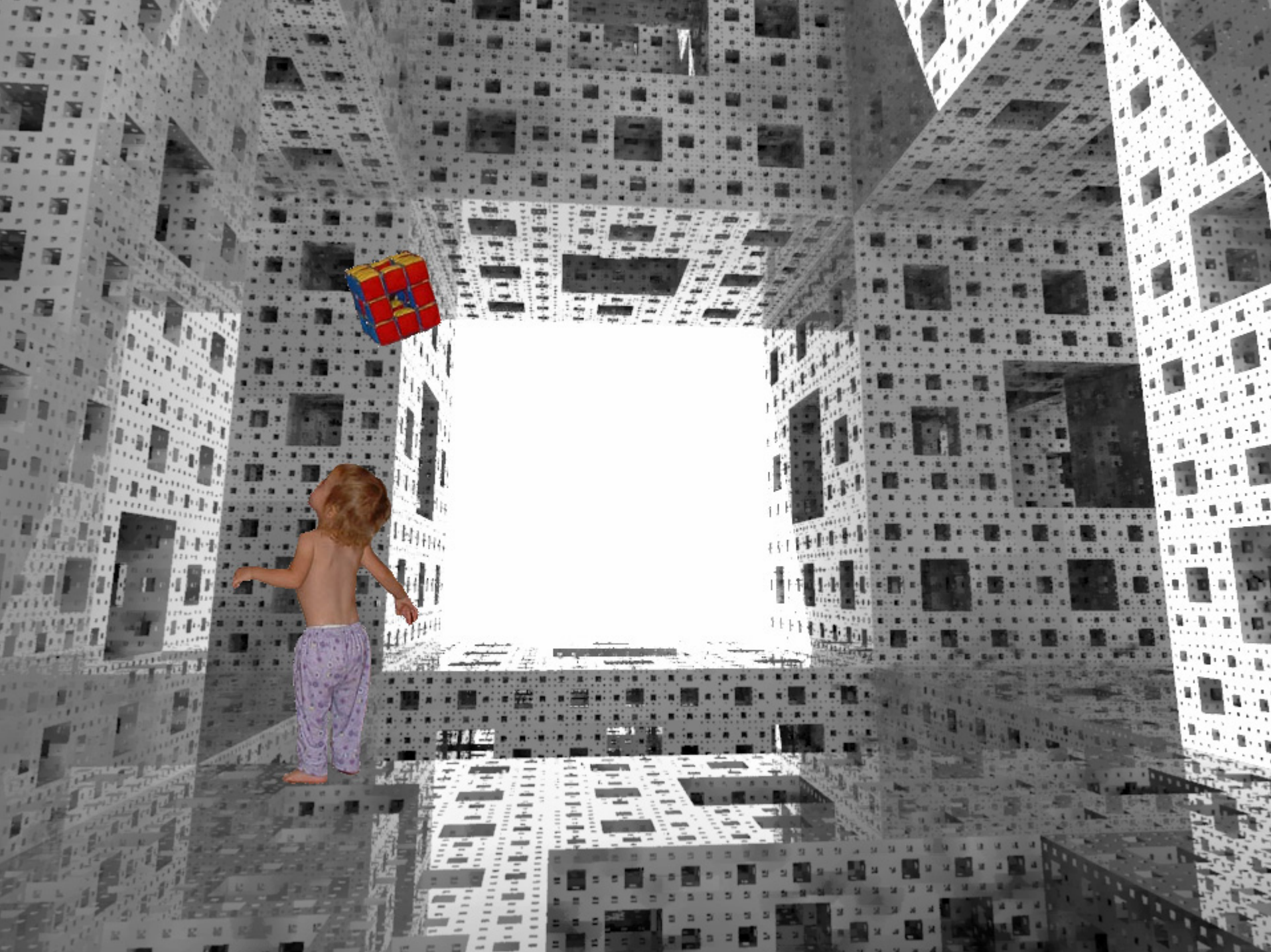
Length analog, the [Cantor Set](#)

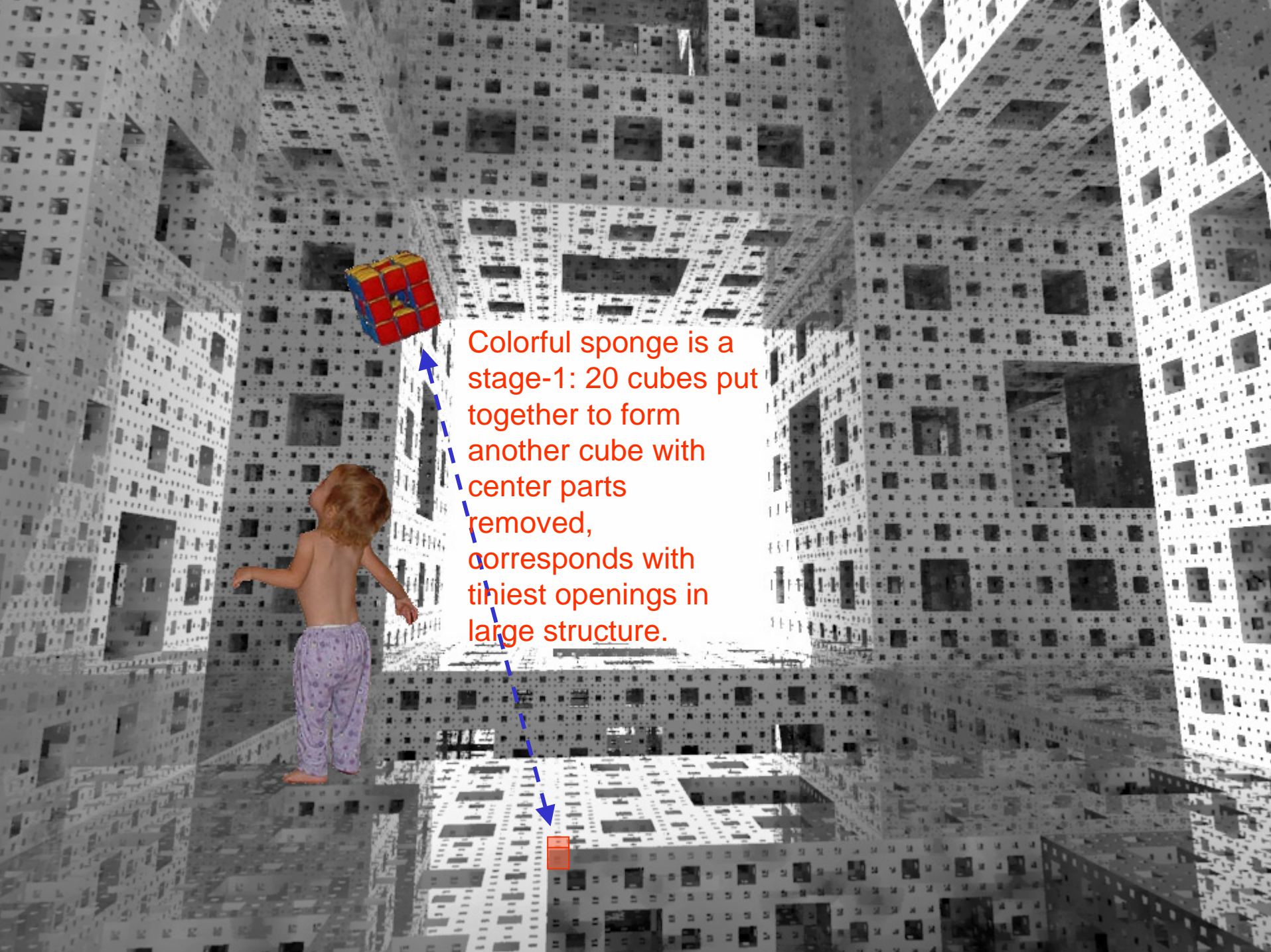


Area analog, the [Sierpinski Carpet](#)

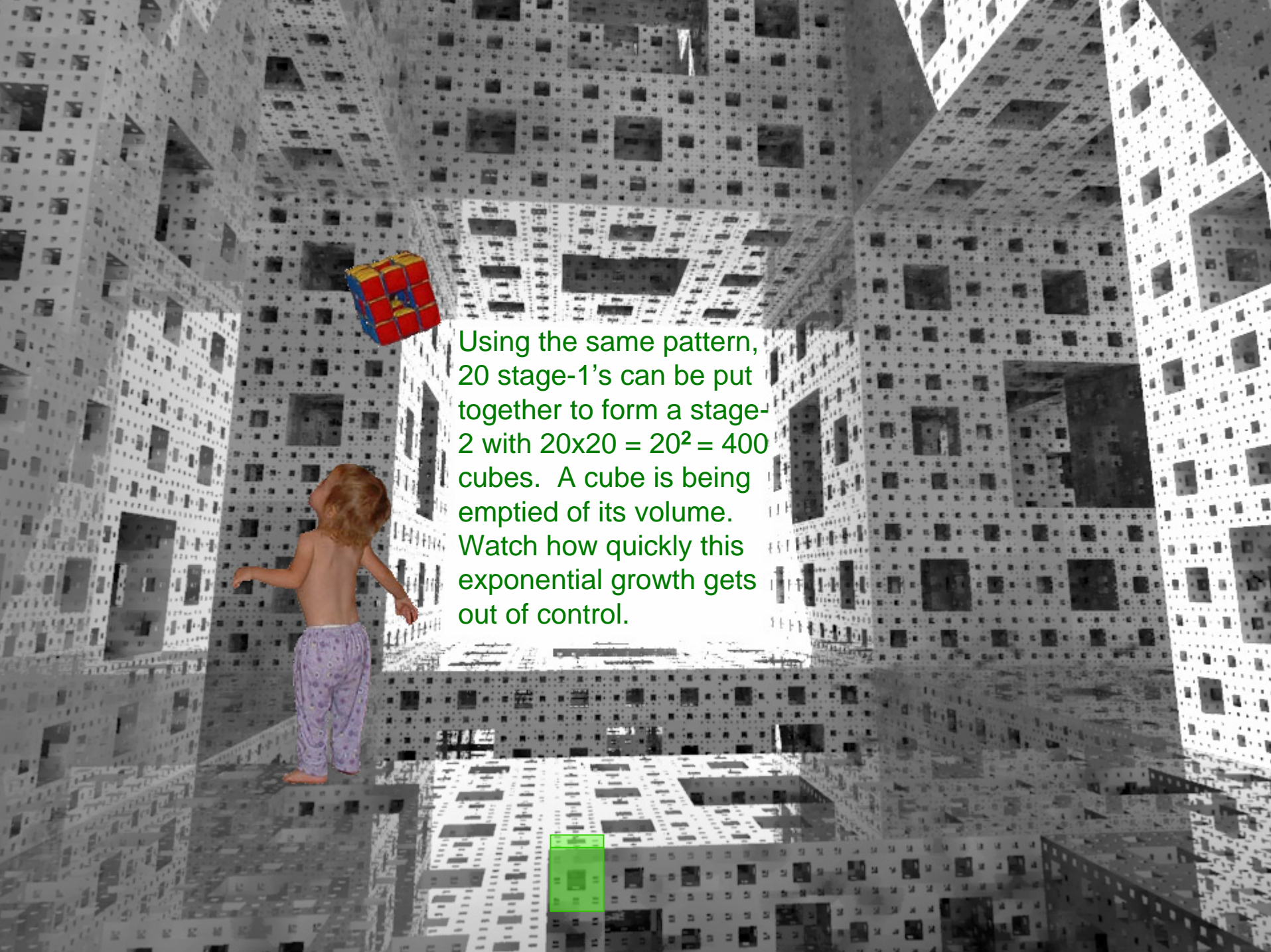


Volume analog, the [Menger Sponge](#)



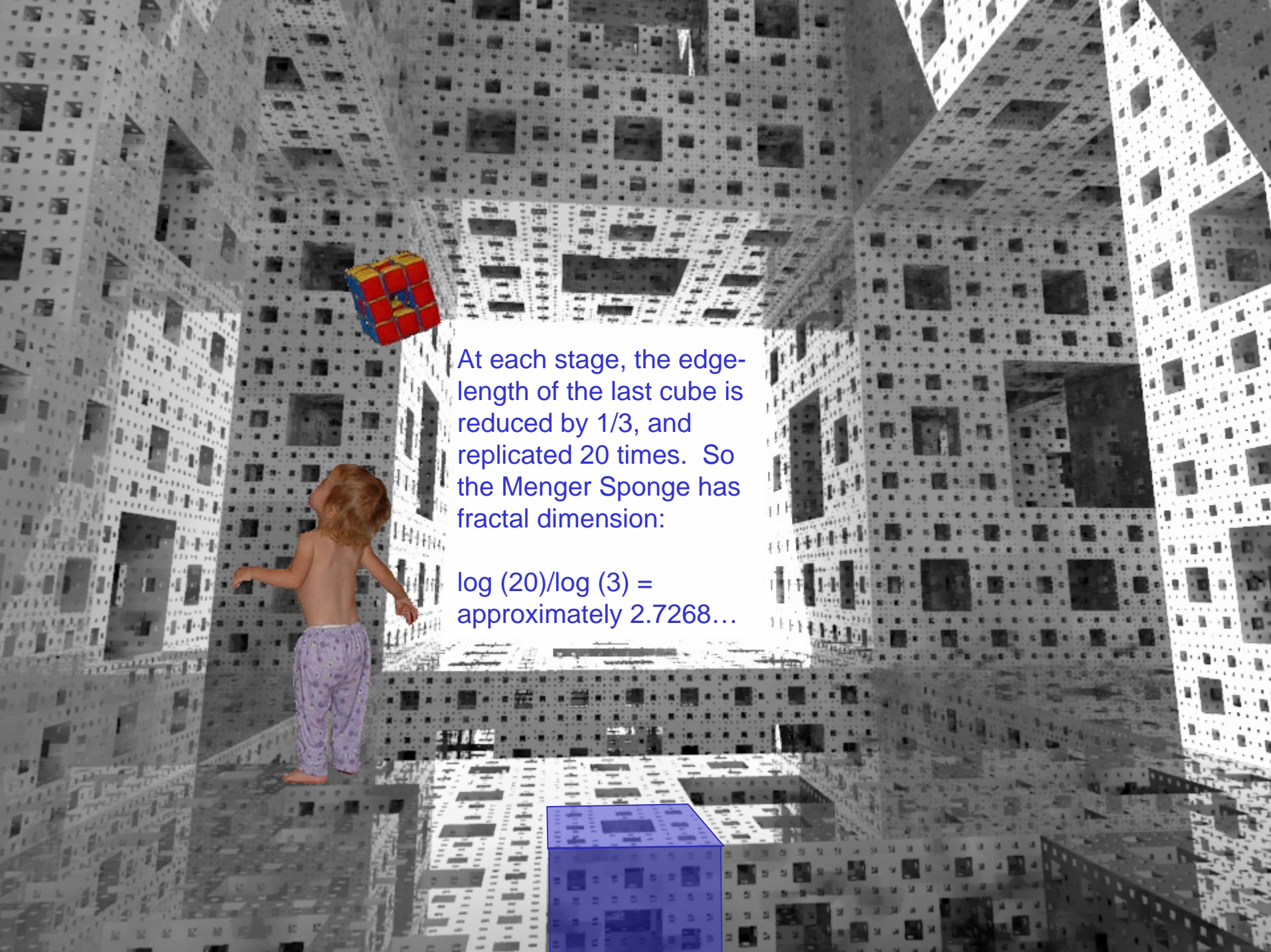


Colorful sponge is a stage-1: 20 cubes put together to form another cube with center parts removed, corresponds with tiniest openings in large structure.



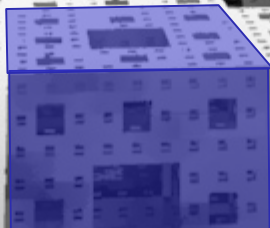
Using the same pattern,
20 stage-1's can be put
together to form a stage-
2 with $20 \times 20 = 20^2 = 400$
cubes. A cube is being
emptied of its volume.
Watch how quickly this
exponential growth gets
out of control.

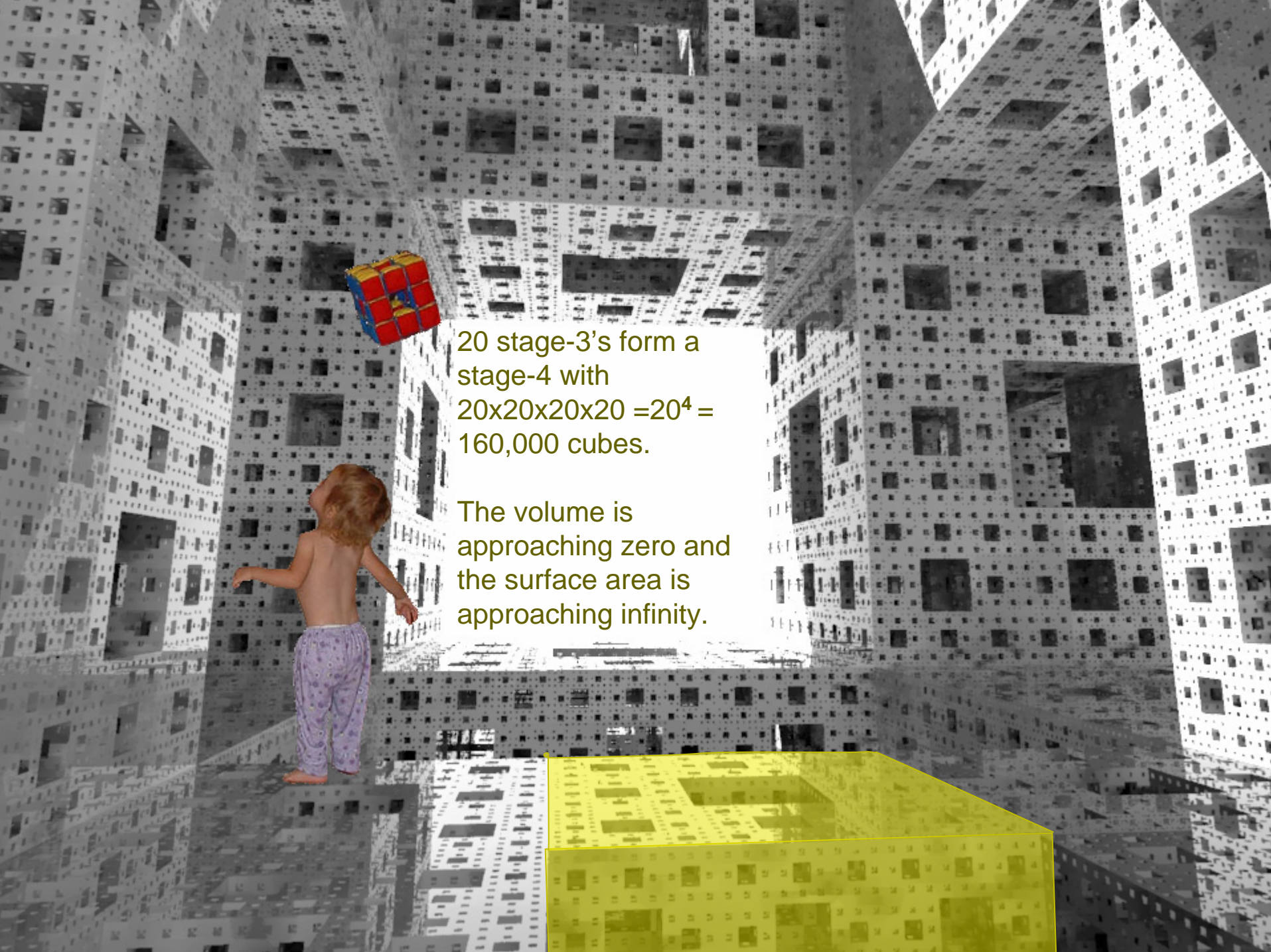




At each stage, the edge-length of the last cube is reduced by 1/3, and replicated 20 times. So the Menger Sponge has fractal dimension:

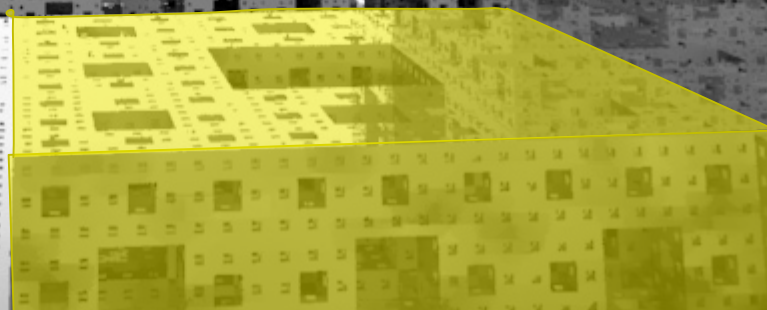
$$\log(20)/\log(3) = \text{approximately } 2.7268\dots$$

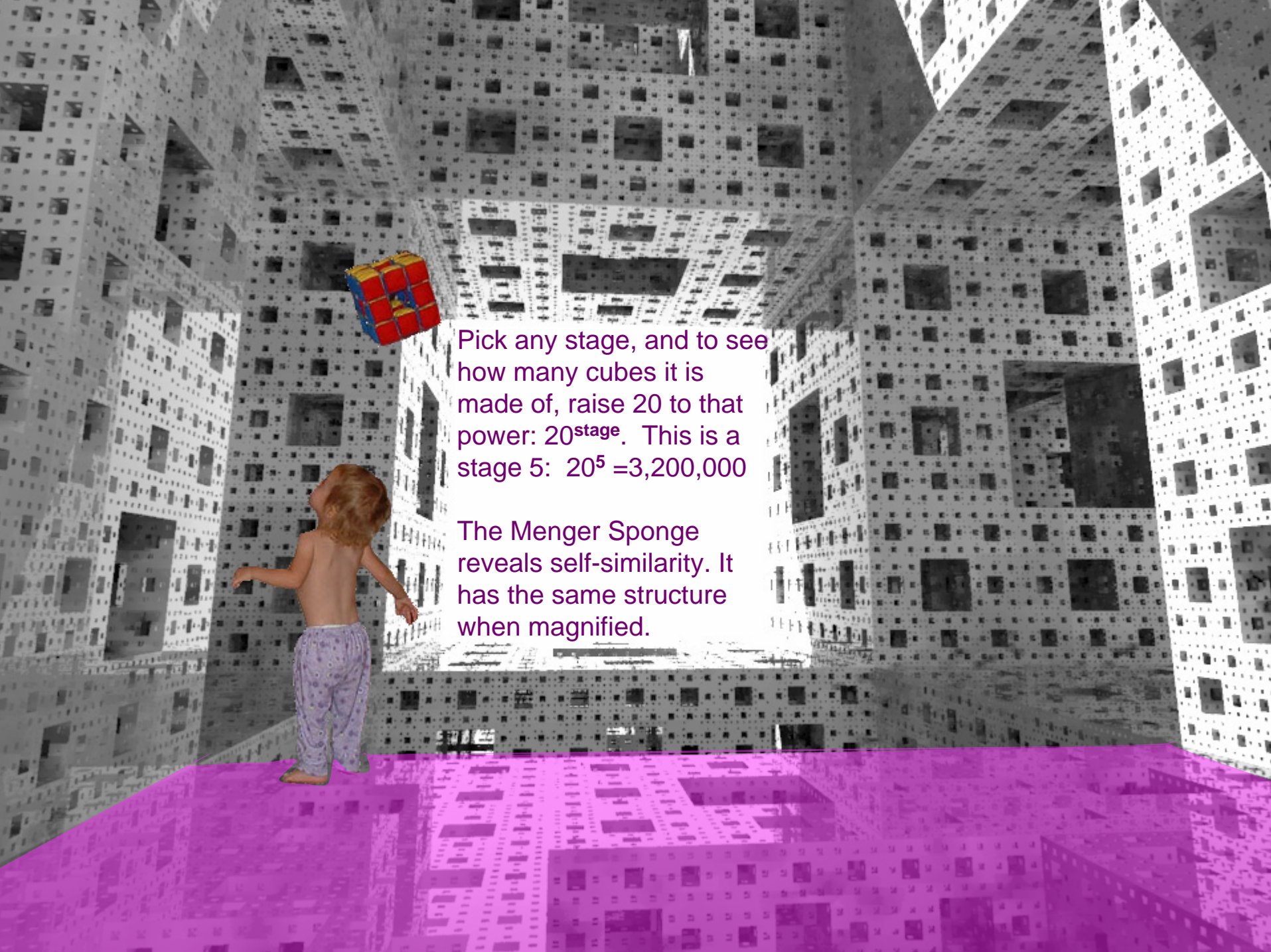




20 stage-3's form a stage-4 with $20 \times 20 \times 20 \times 20 = 20^4 = 160,000$ cubes.

The volume is approaching zero and the surface area is approaching infinity.





Pick any stage, and to see how many cubes it is made of, raise 20 to that power: 20^{stage} . This is a stage 5: $20^5 = 3,200,000$

The Menger Sponge reveals self-similarity. It has the same structure when magnified.

A fractal structure made of cubes, known as a stage-6 Menger cube. The structure is composed of smaller cubes, with some missing to create a porous, lattice-like appearance. A young child with blonde hair, wearing purple patterned pants, stands on a ledge of the structure, looking out. A Rubik's cube is floating in the air above the child. The background is a bright, hazy sky.

How far can this go?
As far as you want it to.
There is no reason to stop here.

This is a stage-6. It is made up of $20^6 = 64$ million cubes.

There is no uncertainty about the way it will grow or what it will look like after any number of stages of growth.

Fractals Across the Disciplines

A selection of topics from the [Yale Fractal Geometry](#) web page [A Panorama of Fractals and Their Uses](#):

Art & Nature

Music

Architecture

Nature & Fractals

Astronomy

Physiology

Finance

Poetry

History

Psychology

Industry

Social Sciences

Literature

(The categories all link to their respective pages.)

Recapping the main fractal theme addressed in this presentation:

Fractals operate under a Symmetry of Magnification (called Dilatation or Dilation in literature). Different types of fractals share a common ground of parts that are similar to the whole. Even though self-similar substructure must technically be present all the way to infinity for something to be called fractal, the concept of fractality is loosened to apply to forms (esp. natural) with only a handful of levels of substructure present.

The simplification of complexity leading to useful results that we have been looking at is not unique to the field of fractals, it is a theme that runs throughout mathematics, although the methods of simplification vary.

“Mathematics is about making clean “simplified” concepts out of things that we notice in the world around us. In the world [staying with fractals as an example], when it is applicable we make a clean concept by assuming the existence of self-similarity—infinite levels of substructure—when there are only a few, pushing beyond reality.” (*Priscilla Greenwood, Statistician and Mathematical Biologist at Arizona State University*)

Math “works” because these simplified systems “work”.
Mathematicians could well be called The Great Simplifiers.