

THE MUSEUM OF MATHEMATICS (MOMATH) – THE NEXT GENERATION OF SCIENCE MUSEUM

Daniel Short and Allison Peters report on this new development in New York that seeks to foster interest in mathematics

Introduction

As literature and history use English, science uses mathematics. Mathematics is a language, not a “science.” It transcends and predates science; and as shown by Paleolithic tally sticks, all known languages (Brooks and Smith, 1987). The United States is consistently placed low on the global education rankings (OECD, 2014; TIMSS, 2014). Consequently mathematics has something of an image problem. It is often seen as hard, abstract - even pointless. Mathematicians love a challenging problem, and the Museum of Mathematics (MoMath) is the solution of one group of mathematicians.

MoMath is located at the north end of Madison Square Park in Manhattan. The museum opened in December 2012. It currently houses 30 exhibits in 19,000 square feet of space. As the name museum implies, *MoMath* is not filled with statues of famous mathematicians, or glass cases containing a dusty abacus. Instead, it is intended to be ‘a kind of playground’ that plays with geometry, art, and algorithms (Minzesheimer, 2012). It describes itself as ‘Interactive, hands-on, engaging, and fun’ (Rothstein, 2012).

Designed by a team of both in-house and external academic mathematics geniuses, the exhibits are designed to be pushed, pulled, twirled, and jumped on. *MoMath* co-founder Cindy Lawrence says, ‘Our goal is to get kids excited, and show them the math they’re doing in school is just one tree in a whole huge forest’ (Grossman, 2012). *MoMath* certainly accomplishes that, and more.

The ‘NextGen’ Science Museum

MoMath has joined an ever growing list of more than 17,000 museums across the United States (Minzesheimer, 2012), including 368 Science and Technology themed museums; a huge arena of institutions fighting for public interest in the free-choice learning sector (Falk, 2002). Friedman (2010) classifies the family tree of science and technology museums into 3 categories:

1st generation (conservation, collection, research, training);

2nd generation (public education, conservation, collection, research), and

3rd generation (public education).

Whilst a cursory view of *MoMath* fits this scheme, it breaks the mold in not being a science and technology museum in the strictest sense, its sole focus on mathematics is what makes it stand out from the crowd. Other examples of ‘NextGen’ Science Museums are the *Center for Post Natural History* in Pittsburgh, a museum devoted to the genetic modification of life-forms; and the *Meguro Parasitological Museum* in Tokyo.

The emphasis of *MoMaths* is on exploration of a variety of mathematical phenomenon at various knowledge levels. Whereas science museums employ a mixture of vivid, sometimes small, often large-scale demonstrations with limited visitor interaction, each and every *MoMath* exhibit allows visitors to interact with that principle, resulting in a visceral learning experience.

Genesis

One of the world’s first museums devoted solely to Mathematics was the ‘*Goudreau Museum of Mathematics in Art and Science*’ on Long Island (1980-2006). The museum featured many mathematical games and puzzles built by mathematics teacher Bernard Goudreau and his former students. At the time it was the only museum in the US dedicated to mathematics. In response to the closing of the *Goudreau Museum* a group of interested parties met to explore the opening of a new museum. This group, led by the museum’s current executive director Glen Whitney, decided to open their museum in New York City. The group raised over 22 million dollars in under four years. Whitney, a former mathematics professor and hedge-fund analyst, calls *MoMath* ‘a safe place to love math’ (Stewart and Skinner, 2012). *MoMath* represents \$6 million in renovations, \$9 million in exhibits and a projected \$3 to \$4 million yearly operating budget. (Dillon, 2012). Prior to opening in December 2012 the creators of *MoMath* estimated that they would have 60,000 visitors a year. Two months after opening they had already clocked over 25,000. In March 2014 it was reported that *MoMath* had 173,225 visitors in 2013, with a projected 90,000 for 2014 (Agovino, 2014; Wallis, 2014).

MoMath inhabits two levels, first floor and basement, comprising 19,000 square feet of 11 E 26th St, New York. Whilst all exhibits were designed especially for the museum, two of the 34 exhibits *Hyperhyperboloid* and *Edge FX* have their roots in ‘*Mathematica: A World of Numbers and Beyond*’ which was part of the IBM pavillion at the 1964 New York World’s Fair. One of several copies of the original *Mathematica* is currently on display at the New York Hall of Science.

Younger patrons are likely to by-pass the instructions provided with each exhibit and immediately start interacting with exhibits. Like science museums *MoMath* uses exhibit helpers, so-called ‘*integers*’ on each floor to keep participants engaged. For more enquiring minds the Touch Screen Display (TSD) accompanying each exhibit contains a brief introduction on the first screen, and further content screens which go into more depth on the topic. The material is laid out both textually and graphically in such a way that it is quickly read and understood. The TSDs are also set up to interface with Radio-Frequency Identification (RFID) equipped admittance cards and social media; such that a user can directly upload any screen shots of their work to the internet.

Exhibits

We have attempted to group the *MoMath* exhibits by categories, and the appropriate grade levels. When we visited the museum in the spring of 2013 there were a total of 34 exhibits, 15 on the upper floor and 19 on the lower floor. *Coaster Rollers*, *Rhythms of Life*, and *Edge FX* were non-functional at the time of our visits.



Function Dilations, Translations, and Reflections	
Pre-Algebra 7 th – 9 th	Logo Generator – Morph symbols using symmetry to create a logo Mathenaeum – Transform shapes into three dimensional sculptures Formula Morph – Exploring how three-dimensional formulas change with different variables
Patterns/Symmetry	
All ages	Light Grooves – Changing the image shown based on the angle of the light Pattern Mesh – Rotate patterns to create new ones Water Frieze - Symmetry Polypaint – Create artwork using symmetry Pattern Paints – Exploring symmetrical Patterns
Cross Sections	
Geometry Area of a 3D figure 7 th - 11 th Grade Finding Volumes – Calculus	Wall of Fire – Cross sections In Plane Sight – View cross sections to determine the 3 dimensional shape 3D Doodle – Two dimensional cross- sections create a 3D shape
Fractals	
8 th grade Factor Tree (GCF, LCM)	Feedback Fractals – Fractal pattern Human Tree – Fractal Tree
Tessellations	
Geometry 7 th – 11 th	Tessellation Station – Tiling patterns Tile Factory – Create tessellations
Music/Waves	
All ages Fractions, Elementary Waves and frequency	Rhythms of Life – Fractions and music Harmony of the Spheres – Music waves
Games/Strategy	
Addition Strategy	Finding Fifteen – Strategic game Math Square – Varying games Shape Ranger – Area Sixth Sense – The number predicts what the sum will be before you choose
Patterns of Pathway	
All ages	Coaster Rollers- Diameters of a circle Square Wheeled Trike – Smooth ride, how depending on the track Twist 'n Roll – How the shape affects how they roll
Key Exhibits	
Hyperbolic functions – Trig, calculus, engineering (bridges, catenaries) Recreational mathematics	String Product – Multiplication Hyper Hyperboloid – Curved surface made out of straight lines Seeing Math – World real applications of math Tracks of Galileo – Find the fastest path down the track Enigma Café – Varying (direct result of puzzles at Goudreau Museum).
Additional Exhibits	
	Time tables – Pythagorean theorem and other puzzles Edge FX – Statistics, probability, profit? Shapes of Space – Creating oddly shaped shapes Structure Studio – Create structures using toys

Function Dilations, Translations, and Reflections

Mathenaemum is a computer-aided sculpture studio, see Figure 1, which utilizes Jules Verne inspired controls to select various geometrical parameters for a design. The exhibit features a *Z Corporation*, now *3D Systems*, colour 3-D printer which is used to build the designs. Designs are voted on each month and the winner is 3-D printed in colour and displayed within the exhibit.



Figure 1 *Mathenaemum*, a 3-D sculpture studio.

Formula Morph utilizes dials and levers to change the function, x , y , and z co-ordinates of shapes on the screen. *Formula Morph* was built by *Moey, Inc.* While the mathematical concept of functions is dealt with by these two exhibits it is approached in a more advanced way in *Formula Morph*.

Patterns and Symmetry

At first glance *Pattern Mesh* appears to simply be an interesting way of placing patterns together, see Figure 2a, and this belief is supported further by the information presented on the *MoMath* TSD. The *At a Glance* screen defines a *moiré pattern* as placing two similar patterns on top of another thus creating a new pattern. But, instead of delving deeper into the mathematics behind these patterns it states '*often, if you move one pattern over another, the moiré pattern they create seems to shimmer*'. The continuing screens then begin to describe how such *moiré patterns* can even form concentric circles or ellipses, although interesting and contain mathematical terms, the science behind this formation is not mentioned.

The best mathematical reference comes at the end of the *Uses* screen where it says '*engineers use... (moiré patterns)...to detect changes that might occur*

on equipment due to stress and strain.' Yet still there is no further elaboration. This statement informs visitors they are used by engineers but could be shown by a simple picture, see Figure 2b, illustrating how a slight misalignment of parallel lines can be easily detected through the extremely visible *moiré pattern* created when placing vertical parallel lines on top of slightly skewed parallel lines.

Furthermore, the fact that *moiré patterns* can be represented in the form of trigonometric functions is never even mentioned. Although a difficult topic to grasp, the mission of *MoMath* is to '*enhance public understanding and perception of mathematics*'. They are effective at capturing the attention of visitors, but fail to optimize on this moment by exposing them to any of the mathematics behind it. On the whole, trigonometry in general is strangely absent from the museum.

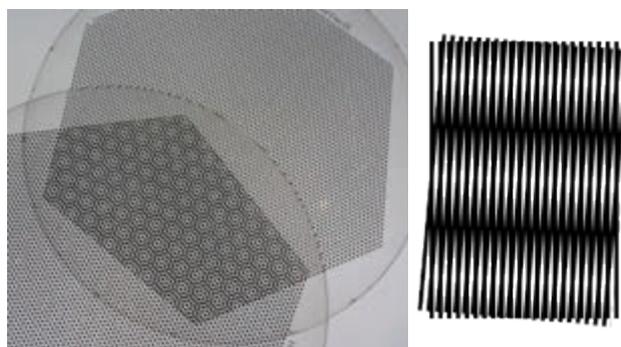


Figure 2 (a) *Pattern Mesh* - A *moiré pattern* formed by overlying dot patterns, and (b) two sets of parallel lines, one set inclined at an angle of 5° to the other.

Light Groves, *Poly Paint* and *Pattern Paints* explore the same concept in a visual manner, see Figure 3.

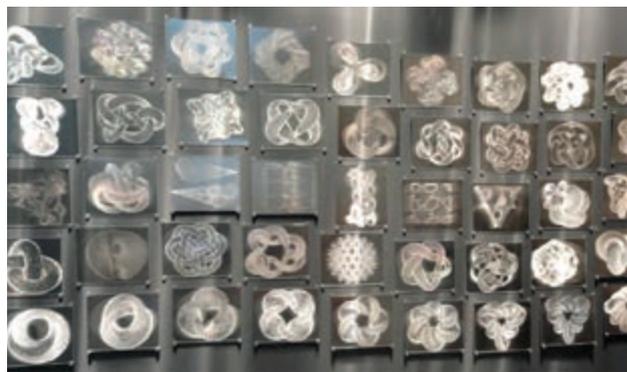


Figure 3a *Light Groves*



Figure 3b *Poly Paint* Image ©Blue Telescope Studios.



Figure 3c *Pattern Paints* Image ©Blue Telescope Studios.

Cross Sections

Wall of Fire, *3D Doodle* and *In Plane Sight* are a series of three exhibits that all allow users to ‘slice’ 3-D shapes in order to see the polygons that comprise each shape, see Figure 4. This slice is referred to as a cross section. Cross sections are used in many different applications in the real world including medical imaging, culinary arts, and geography. However, one of the main mathematical applications is taught in calculus when examining how to calculate the volume of a function when rotated around an axis. By slicing a three-dimensional polyhedron you can often obtain a cross section which can be used to more easily calculate the volume of the polyhedron.

These three exhibits can be combined to develop the schema of cross sections in a visitor’s mind. *Wall of Fire* can be used to introduce the concept of cross sections, and to create and test hypotheses about what shape each cross section will be. Through questioning, students can even discover that ‘slicing’ three-dimensional figures along different axes may result in different shaped cross sections. Visitors can then explore *3D Doodle* in which they can apply the knowledge they just gained to complete a puzzle by piecing together various cross sections to create a three-dimensional shape. Since the shapes displayed here are regular it should be an easy transition from hypothesizing about what a cross section will look like to determining where each slice fits. Once mastered, visitors can then examine *In Plane Sight* where they are able to virtually examine an irregular three-dimensional figure at various angles to correctly identify the item. This exhibit is not ‘slicing’ the three dimensional objects, but instead is showing the outermost slice at different angles. Visitors then have to piece together the images to build the object in their head and select the correct object.



Figure 4 *3D Doodle*

All three of these exhibits turn abstract concepts into reality in a fun and exciting way. Through the use of technology the exhibits allow students to manipulate real, and virtual, objects in ways that allow them to develop schemas for mathematical concepts through discovery.

Fractals

Feedback Fractals, see Figures 5a and 5b, provides an opportunity for the user to experience a fractal world. Fractals are objects which are not smooth or regular, see Figure 6. The word fractals was coined by Mandelbrot and comes from the latin word *fractus* meaning broken or fractured. Many fractals have self-similarity, meaning that you can zoom in on an object and see the image repeated again and again. Each camera in feedback fractals defines an affine map, which is a geometrical construct specifying a translation, a rotation, a shear and a scaling of the image.

Real world shapes such as the leaves of a tree, see Figure 5b, resemble fractals much more than they resemble regular shapes such as cones, cubes, spheres etc., however real world shapes are not exactly self-similar but display more randomness. Introducing such randomness into computer simulations of mathematically generated fractals used in movies for special effects of fire, rain, smoke etc. produces a more realistic image. Glen Whitney describes *Feedback Fractals* as showing the basics of mathematics ‘...the understanding that there is a repeating pattern, and that is at the root of all mathematics’ (Souccar, 2012).

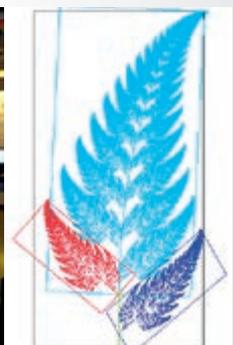


Figure 5 (a) *Feedback Fractals* Figure 5 (b) *tree leaves exhibit fractal patterns (RHS image of the Barnesley Fern from Wikipedia).*

One of the stand-out exhibits at *MoMath*, *Human Tree* creates a fractal tree, where each branch is a smaller version of the tree, see Figure 6. The exhibit models self-similarity, where a smaller piece of the object looks like a miniature copy of the entire object. Examples of self-similarity in nature include trees, mountains, and coastlines. The *Human Tree* was developed by Theodore Gray using the software program ‘*Mathematica*’. The exhibit was developed for *MoMath* by *Blue Telescope Studios*.



Figure 6 *Human Tree*. Image ©Blue Telescope Studios.

Tessellations

Tessellation Station provides a variety of shapes that can be arranged in a unique way such that none of the sides overlap, and that there are no gaps between each shape, or in other words, such that they tessellate, see Figure 7. While a nearby accompanying exhibit called *Tile Factory* allows visitors to design their own tessellating shapes. Both of these exhibits educate visitors about the geometric properties behind tessellations through a hands-on approach.



Figure 7 *Tessellation Station*

MoMath does an excellent job providing examples of the uses of tessellations along with an array of photos in an attempt to intrigue visitors to explore each station, and to delve deeper to discover how mathematics can be transformed into such a beautiful art form.

Music

The *Harmony of the Spheres*, the centerpiece of the lower level, allows visitors to experience the connection between music and mathematics, see Figure 8.

The *Harmony of the Spheres* can be touched to generate musical notes and make music. Major and minor chords, and harmonies can be generated. The exhibit was designed in collaboration with Dmitri Tymoczko and built by Moey, Inc.

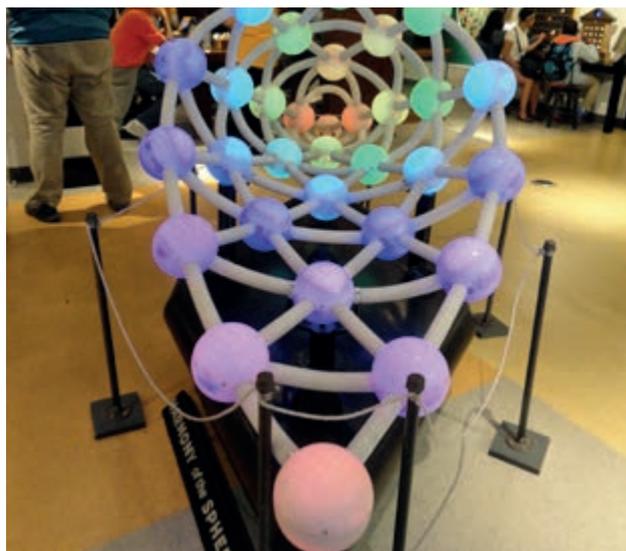


Figure 8 *The Harmony of the Spheres*

In *Rhythms of Life* participants fill turntables with fractions of a disc that add up to one, see Figure 9. Each fraction represents part of a rhythm that plays a sound selected from the sound archive, plastic blocks with RFID tags. Combining the turntable leads to a combination of sounds allowing the rhythm maker to experience the combining of sounds to form more complex patterns.



Figure 9 *Rhythms of Life*

Strategy Games (Addition Strategy)

Addition strategies are approaches to solving addition problems. There are three strategies to addition; *count up*, for example $14+3 = 15$, 16, 17, *doubles*, for example $2+2$, and *tens*, for example: $1+9 = 10$, $2+8 = 10$, $3+7 = 10$, etc.

In *Finding Fifteen* the participant takes turns with an opponent selecting numbers from 1 to 9 in order to be the first to have three numbers that add up to 15, see Figure 10. Players take turns pulling levers and must pull a total of 3 levers that add up to 15 to win. The opponent has the exact same levers to pull and cannot pull levers already played. If no opponent is available you play against the computer.

A computer simulation of this game is available at <http://www.primarygames.com/math/make15/>.

There is a strategy to this game which becomes apparent after several turns.



Figure 10 Finding Fifteen

Finding Fifteen is related to the 'Lo Shu Square', or the 'Nine Halls diagram', see Figure 11. The exhibit fails to mention this important connection to ancient Chinese culture. *Lo Shu* is part of the legacy of ancient Chinese mathematical and divinatory traditions, and is an important emblem in Feng Shui, the art of geomancy concerned with the placement of objects in relation to the flow of energy. Furthermore, the connection between *Finding Fifteen* and the contemporary maths puzzle 'Sudoku' is apparent.

4	9	2
3	5	7
8	1	6

Figure 11 Lo Shu magic square

Math Square is a huge computer screen that you can walk on, see Figure 12. The square demonstrates: Voronoi cells, least total length of line segments, and puzzle games. The configuration of *Math Square* has similarities with 'Near' an exhibit at the New York Hall of Science.



Figure 12 Math Square by Moey, Inc.

Shape Ranger is a game where the user attempts to organize 2-dimensional shapes into the smallest area possible, see Figure 13. This exhibit uses a multi-touch table which identifies the shapes and computes the area around them. Packing problems are a class of optimization problems in mathematics that attempt to pack 3-dimensional objects together into containers. The goal is to maximize 'packing efficiency' either by minimizing the volume used to pack a single container as densely as possible, or to pack all objects using as few containers as possible.



Figure 13 Shape Ranger. Image ©Blue Telescope Studios

The real life connection, which is not very well stated by the exhibit, as to why packing is important; is that 'packing problems' can be related to real life packaging, storage and transportation issues. Packing of irregular objects like those used in *Shape Ranger* is a problem not lending itself well to closed form solutions; however, the applicability to practical environmental science is quite important. For example, irregularly shaped soil particles pack differently as the sizes and shapes vary, leading to important outcomes for plant species to adapt root formations and to allow water movement in the soil.

Sixth Sense predicts how your numbers add up and is designed to mystify the user, asking them to question how it works, see Figure 15. In the large 6 x 6 version of *Sixth Sense* one number from each of six columns and rows is selected and always adds up to 111, whilst in the smaller 4 x 4 version the numbers always add up to 34. The exhibit uses the principle of magic squares much like *Finding Fifteen*. The idea for *Sixth Sense* came originally from Martin Gardner, author of the 'Mathematical Games' column published in Scientific American for 25 years (Henebry, 2012). *Sixth Sense* was built by Moey, Inc. using vacuum tubes to display the integer values giving it a vintage and well used feel.



Figure 15: Sixth Sense

Patterns of Pathways

Coaster Rollers is an exhibit that consists of a cart, sitting atop a tray full of rubber shapes resembling acorns. These forms are carefully chosen to be 'surfaces of constant width', a shape whose highest point is always the same height above a table, no matter which way you turn it. The sphere would be the most well-known example, but it turns out there are an infinite variety of shapes with the same property.

Square Wheeled Trike allows smaller patrons to ride a square-wheeled tricycle on a bumpy track, yet still have a smooth ride, see Figure 16. It has to do with a track made of catenary curves that keep the wheel axles perfectly level.



Figure 16 *Square Wheeled Trike*

With *Twist n' Roll* various shapes on the table can be split into two pieces and reconnected via magnets to form different shapes, see Figure 17. The new shapes roll along different paths. The goal is to build a shape which makes each of the paths shown on the table.



Figure 17 *Twist and Roll*

Key Exhibits

String product is a 23 foot paraboloid, 3-D parabola, and interactive calculator, see Figure 18. *String Product* has been constructed between the two floors of the museum, spun around a central pole to make a 3-D sculpture. The shape is laced with ropes of lights that run between points on the paraboloid where the radius is a whole number (Grossman, 2012). Two panels of integer value buttons are used to create a multiplication. The strings originating at those numbers meet each other at the central axis at exactly the product of those numbers.



Figure 18 *String Product*: A Google Inc. sponsored interactive mathematical sculpture.

Hyperhyperboloid sculpture is made from two sets of straight line cables and a chair mounted on a spinning platform, see Figure 19. When the chair is turned the angle of the cables changes and the hyperboloid begins to take shape. From the inside you get a different perspective. The exhibit is designed so that the user experiences the surprise of straight lines turning into a complex shape, the hyperboloid. Hyperhyperboloid, more properly called the hyperboloid of one sheet, is doubly ruled, through every one of its points there are *two* distinct lines that lie on the surface. The exhibit does not mention how the parabola relates to the real world, such as constructing hyperboloid structures, for example a power-plant cooling tower built using only straight steel beams. Hyperboloid structures are characterized by their minimal use of materials, time and labour.



Figure 19 Hyperhyperboloid

In *Tracks of Galileo* students explore slopes and functions, see Figure 20. Students can analyze their results to find the fastest possible path, or to compare their average race times with the results of their classmates.

The question that this exhibit is based on is Johann Bernoulli's '*Brachistochrone Problem*', which examines the curve that will allow an object to slide from one point to another in the least amount of time. Later versions of the same problem formed the basis for Euler's '*Calculus of Variations*' and Lagrange's '*Infinitesimal Calculus*', methods for the determination of maxima and minima of functions. While students may not be ready for calculus yet, they can still think about this question.

Galileo first posed this problem in 1638, thus the exhibit bears his name. Galileo proposed that a circle arc would be a faster path to travel over a straight line segment. The exhibit allows the user to test these theories. Galileo then proposed that the circle arc would be the quickest path, an incorrect deduction.

In the solution, an inverted cycloid, the bead may actually travel uphill along the cycloid for a distance, but the path is nonetheless faster than a straight line or circle arc.



Figure 20 (a) *Tracks of Galileo*

Enigma Café is a collection of recreational mathematics puzzles, many of which are sold in *MoMath*'s shop, see Figure 21. Examples include: 6-Cushion Shot, 15-Puzzle, 4 Ts Puzzle, Iron Heart, Iron Maiden, Kites and Darts – a periodic Penrose tiling, Patience Puzzle, Peg Solitaire, Pentominoes, Rubik's Cube, Rush Hour, Tangrams, and Tetraxis.



Figure 21 *Enigma Café*. RHS Image ©Blue Telescope Studios

Additional Exhibits

Edge FX displays a succession of random independent results. It is the latest version of the '*Probability Machine*' or Galton board. An original model '*Probability*' was an exhibit that was included in '*Mathematica: A World of Numbers and Beyond*' for the IBM exhibit at the 1964 New York World Fair, it is currently on display at the New York Hall of Science. An update to the classical probability distribution model is a lever that enables the participant to select where the balls will fall. The digital display keeps track of how many balls land on the right side, and how many land on the left side. By changing the bias, lever position, users can see that the distribution matches the bias that has been set.

Discussion

There are over 18,000 museums in the US. Manhattan, with 181 museums, is America's museum capital (Ettle, 2006). What makes *MoMath* special is a combination of its uniqueness and state-of-the art exhibits; some of which work extremely well, whilst others leave much to be desired (Rothstein, 2012). *MoMath* opened with 34 exhibits, 45 were originally planned (Souccar, 2012). The majority of these are described in this article.

What surprised us most about *MoMath* is the lack of diversity in the exhibits in the first year of opening. A curious lack of exhibits devoted to 'pi', 'e', logarithms, trigonometry; and the theorems of Pythagoras, Fibonacci or Euclid. What is clear is that the focus from the start was on exhibits that engage the user, which *MoMath* readily admits (Adams, 2013). President and co-executive director of *MoMath* Cindy Lawrence has stated that it was difficult at first to decide how much detail and level of explanation to provide.

In order to assess the success of *MoMath* in attracting paying visitors it is useful to compare it to similar institutions, namely science and discovery centres. The size of science and discovery centres obviously has an impact on visitor numbers (Short and Weis). The size varies from around 1,000 square feet (Explorit Science Centre, California) to over 700,000 square feet (Science Museum, London). Examining the on-site visitor numbers normalized to their respective size results in what is called the 'performance ratio'; this number is on average six visitors per square foot (for US locations in 2011) and increases linearly with increasing operating expense (ASTC, 2011). With 173,000 visitors in the first year the performance ratio for *MoMath* is a respectable 9.1 visitors per square foot (173,225/19,000). Surprisingly, the performance ratio for centres around 50,000 square feet does not significantly change with the size of the centre. For science and discovery centres over 50,000 square feet the performance ratio may increase to around ten, but in many cases remains less than 2-3 visitors per square foot (Groves, 2005). *MoMath's* projected performance ratio for 2014 is expected to decline to a still healthy 4.7 visitors per square foot when its 'newness' or novelty value wears off over time.



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Note

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References

Adams, C. (2013) Museums Open Doors to New Ways of Learning Math. *Education Week*, Vol. 32, No. 33, pp 8.

Agovino, T. (2014) Math Museum Multiplies and Prospers. *Crain's New York Business*. March 3rd. URL: <http://www.craigslist.com/article/20140303/ARTS/140309984/math-museum-multiplies-and-prospers#>. Accessed 04/02/2014.

Association of Science and Technology Centers (2011) Washington D.C. *ASTC Statistics Analysis Package*.

Brooks, A.S. and Smith, C.C. (1987) Ishango revisited: new age determinations and cultural interpretations. *The African Archaeological Review*, Vol. 5, pp. 65-78.

Dillon, K. (2012) *MoMath* No Problems: North America's Only Math Museum Now Open in Madison Square. *New York Observer*. Mon, 17 Dec 2012.

Ettle, J.L. (2006) Irrational Exuberance: Calculating the total number of museums in the United States. M.A. Thesis, Baylor University. URL: https://beardocs.baylor.edu/xmlui/bitstream/handle/2104/4196/joseph_ettle_masters.pdf. Accessed 03/31/2014.

Falk, J. H. (2002) The contribution of free-choice learning to public understanding of science. *Interscienca*, Vol. 27, No. 2, pp. 62–64.

Friedman, A. J. (2010) The evolution of the science museum. *Physics Today*, Vol. 63, No. 10, pp. 45–51. URL: www.physicstoday.org/resource/1/phtoad/v63/i10/p45_s1?bypassSSO=1. Accessed 03/31/2014.

Grossman, L. (2012) MOMATH: Manhattan's Museum of Mathematics. *New Scientist*, Vol. 216, No. 2894, pp. 50.

Groves, I. (2005) Assessing the Economic Impact of Science Centers on Their Local Communities. Questacon: The National Science and Technology Center. Visited: Feb 2013. URL: <http://www.astc.org/resource/case/EconImpact-whole.pdf>. Accessed 03/31/2014.

Henebry, C. (2012) The making of *MoMATH*: America's only Museum of Mathematics. *Math Horizons*, Vol. 20, No.2, pp. 14-17.

Minzesheimer, B. (2012) *MoMath* offers proof that math can be fun, cool. *USA Today* 12/14/2012.

Rothstein, D. (2012) Opening the Doors To the Life of Pi. *New York Times*. 12/14/2012, p23. Op.

Short, D.B. and Weis, N. (2013) The role of science & discovery centres in the public understanding of science. *School Science Review*, Vol. 95, No. 350, pp. 27-38.

Souccar, M.K. (2012) Exec hopes math museum adds up. *Crain's New York Business*, Vol. 28 No. 29, pp. 0026

Stewart, I. and Skinner, L. (2012) Do the Math. *Smithsonian*, Vol. 43, No. 3, pp. 108.

OECD (2014) Organization for Economic Co-operation and Development: <http://www.oecd.org/pisa/pisaproducts/pisa2009/>. Accessed 03/31/2014.

TIMSS (2014) Trends in International Mathematics and Science Study: <http://www.timss.org/>. Accessed 03/31/2014.

Wallis, D. (2014) Start-Up Success Isn't Enough to Found a Museum. *New York Times*. URL: http://www.nytimes.com/2014/03/20/arts/artsspecial/start-up-success-isnt-enough-to-found-a-museum.html?_r=0. Accessed 04/02/2014.

Wikipedia (2013) URL: http://en.wikipedia.org/wiki/Barnsley_fern