Master's Thesis

TIME IN THE DIGITAL AGE OF ARCHITECTURE

by

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ABSTARCT

Though many researches exist about the notion of movement as an ideal in modern architecture, little is said about time and movement in architecture in the context of its digitalization. This paper addresses the architectural representation of time in the Digital Age. The relations of the temporal dimension of space are examined in art, sciences and philosophy in order to better explore the translation of this phenomenon in architecture. Art, science and all culture of the beginning of the XX th century began with new ways of conceiving time and space. Cubism and the theory of relativity for example interpret in their own language distinctively, that space and time are not two absolute entities, Four-dimensional space in art, physics and philosophy involves the concepts of multiplicity, manifold and continuity. These concepts will be explored in relation to architecture.

INTRODUCTION

Space can have many dimensions, time being one of them. Space with more than three dimensions, from four to n, offer new mathematical, artistic, philosophical and architectural changes. Over the past decades research in the field of time in architecture have focused on motion within three-dimensional space, however four-dimensional architectural space in the digital age is still under-explored. This lack of attention is significant because knowing about the notion of time in the digital age of architecture will provide a wider range of semiotic significances to the architectural language. In order to address this issue, this paper explores transformations in architecture that embody the cultural, artistic and scientific shift of the notion of time. New concepts of time and space emerged in cultural movements in the beginning of the XX th century. To illustrate Cubism, relative physics, cinematography and the architectural modern movement were all decisive events that introduced movement as four-dimensional interactions of space and time. The Information Age succeeding the Industrial Age restructures cultural communications in many ways and transforms architecture with the digitalization of its tools in design and fabrication as well as digitally embedded materials. The ability to find new ways to think about reality allows for cultural progress. This progress seems to be a translation of abstract images and notions into a linguistic description. Visual art's language is heavily based on images that usually entails a qualitative relationship of imagination and aesthetics whereas the language of physics uses numbers and equations connected by mathematical relationships and quantifiable properties. These languages describe in their own way the change in the notion of time at the beginning of the 20th-century. This paper addresses the description of this phenomenon in architectural language. How is the new notion of time represented in architecture within the digital age ? How the fourth-dimension and digital technology are related to architecture in relation to design and fabrication? Architectural space and form, from static seems to become dynamic. Perhaps it relates to dynamic digital programs that include the notion of time in design in a new fashion, through animation programs. The introduction of Interactive architecture is also interesting in the fact that it promotes interactions of space and time thus promoting a four-dimensional space-time event. The Digital Age offers the technological infrastructure to include the notion of time in design with animation, in construction with digital fabrication and 4D printing, in structural behavior with interactive architecture.

The impact of such transformations on 20th-century architecture and early 21st is studied in the context of information technology . The scientific notion of time changes in the beginning of the 20th-century when a scientific shift occurs between the physics of Newton and Einstein. Einstein in his theory of Special Relativity, thought about observers traveling at different speeds, who would get the same result when they measure the speed of light, he supposed that to an observer, length contracts and time dilates with increasing speed. In classical science, events must be processed in sequence. In relativity, sequence is not so obvious and at the speed of light there is no sequence at all, at light-speed everything in space-time is simultaneous. Newton's concept of space and time are remodeled by Einstein into one concept of space-time continuum. Even if Einstein's theory is very much influenced by classical physics, many differences separate both theories, notably the use of mathematics. Newtonian physics occur in an geometrically Euclidean space where as the space-time continuum is described mathematically by a non-Euclidean geometry. Coding architecture with different types of geometries produces different types of spaces. We can observe influences of the use of a different geometry in buildings, when non euclidean geometry is used by architects, such as topological or parametric relationships of shapes in the digital design process. This highly contrasts the use of more simple relations of euclidean shapes and of the Cartesian grid associated with the modern architectural movement.

The type of geometry used in the process of architectural design, Euclidean or non-Euclidean, is determinative of the spatial coding in which it will be created. Although the geometry used in the design is different, the tangible architectural object, the form, is always described by an euclidean three-dimensional geometry[1]. Shapes, by not having material properties nor a definitive scale, can have geometrical relations of different types. Forms, for the opposite reasons, cannot. Yet, the type of geometry used, still has repercussions on the build architectural object. Since the conceptual coding of space changes it possibly also changes the semiotic of architecture.

Einstein's “Special Theory of Relativity” and “General Theory of relativity” rely on the fact that spatial relationships are not described by a three-dimensional Euclidean geometry but by a four-dimensional Riemannian geometry. The Riemenian manifold is a mathematical concept of spatiality at the center of the theory of relativity and is also very present in the philosophical work of French philosopher Gilles Deleuze .

Deleuze on his own and then with Felix Guattari, wrote about a philosophy of materiality and multiplicity. The concept of multiplicity is fundamentally linked with classical and relative physics as the important mathematical notions of calculus comes from Newton and Liebniz and the Riemeniann manifold is related to the theory of relativity of Einstein. The philosophy of Deleuze borrows mathematical concepts of space-time such as the Riemannian manifold. Einstein's theory is substantially significant in the shaping of the philosophical concept of time of the 20th century in the technological society. Before Deleuze, Bergson, the influential philosopher of time, also compared his notion of time to the theory of relativity. Since many architects of the end of the 20th-century are influenced by the theoretical works of Deleuze, it seems possible that architects may have encountered the theory of relativity indirectly.

On the other hand, some architects were directly influenced by Einstein from the beginning such as Le Corbusier, Franck Lloyd Wright, Buckminster Fuller and Erich Mendelsohn the architect of the Einstein tower. Some of the above architects encountered Einstein or had him in mind while designing. Le Corbusier (Charles-Edouard Jeanneret) (1887-1965) prominent architect of the modern movement, encountered Einstein at the university of Princeton in 1946 and talked to him about the Modulor. The same evening, Le Corbusier tells us, that Einstein wrote in a letter about the Modulor : “It is a scale of proportions which makes the bad difficult and the good easy”.[2] Frank Lloyd Wright (1867-1959) a pioneer of the architectural movement, also met the physicist for a short period of time. In 1931 the architect send a copy of his book modern architecture to Albert Einstein with the inscription : “To the Supreme Scientist

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1 Our brain and senses are not biologically equipped to understand a fourth spatial dimension.

2 Le Corbusier, *The Modulor: A Harmonious Measure to the Human Scale Universally Applicable to Architecture and Mechanics*. London: Faber & Faber, 1956. p58

Albert Einstein from Frank Lloyd Wright in remembrance of an hour together."[3] Buckminster Fuller (1895-1983) gathered with the author of the theory of relativity in 1936. Buckminster Fuller started to wright his book "*Nine chains to the moon*" in 1933, he asked permission from Einstein's editor to cite some parts of the Einstein's work, which they agreed to. Three chapters of the book are about Einstein. Fuller was persuaded that Einstein's relativity which was based on the speed of light would be "the catalyst of a chain reaction that would eventually change our every day lives.[4]

By the end of the century and the beginning of the 21 st, architecture of the digital avant guard morphologically seems to be characterized by curvature, movement and fluidity, where as the first half of the century is characterized by orthogonal lines, parallel and perpendicular levels. Fluidity has its place within architecture in the beginning of the century still, this is not expressed plastically. The new notion of time affects early the culture within it was created and consequently the architects as well. As Fuller observes, through history, it seems that the scientific academy doesn't accept the discoveries scientists make immediately, nonetheless in some cases later on, they do. It takes even more time for the scientific discovery to introduce itself in school books hence to influence the students before being in the general intellectual atmosphere of the majority of the population.[5] However in the case of the concept of space-time it seems that cultural parameters were introducing the transformation of the notions of time and space such as the Cubist movement for example or philosophers that thought of time as a non-linear phenomenon. Society seems to be predisposed to accept this shift, this seems to explain why many intellectuals were interested in the physical discoveries of Einstein even before their experimental validation.

Even so, the remodeled notion of time doesn't transform instantly, the architects mentioned previously are indeed interested with the theory of Einstein but they are a minority of intellectuals, the new concept of space-time is not a general idea implemented in the technological society yet as in there are no inventions in the industry that are based on Einstein's discoveries. Additionally, architects are restricted by the technological means of architectural representation and construction. The information age brought to the architectural scene, the digitalization of its tools in relation to design and construction. Limitations regarding the fabrication of the building decrease as the construction process is enhanced by computer

3 Milton Cameron "*Albert Einstein, Frank Lloyd Wright, Le Corbusier, and the Future of the American City",* Institute for advanced studies, Spring issue 2014, https://www.ias.edu/ias-letter/cameron-einstein

4 "Le catalyseur d'une reaction en chaine qui finirait par modifier notre univers quotidien" tramslation Katerina Konstantopoulos.

5 Snyder, Robert," *Buckminster Fuller : scénario pour une autobiographie",* traduction Didier Semin Images Modernes 2004.. p.80

numerically controlled machines. A digital fabrication process, as to architecture, is a tool with robotic mechanisms with which architectural parts are produced. The transformation started when the theory of information changed architecture as well as other socioeconomic structures.

The information age, following the industrial age, greatly influenced different sciences as well as architecture. Architecture is fundamentally affected regarding the design and construction of the building transitioning towards a computer based media. Where as architectural design tools were manually driven for the most part of the 20th century, since the dusk of the previous millennial, they now are digitalized with use of computer aided design (C.A.D). Although the tools in design remained operated by hand for many centuries, it is worth noting the use of the computer in architectural practices is constantly increasing. Pioneer of the use of computational softwares in Architecture is Franck Gehry with the use of Computer aided Three-dimensional Interactive application (CATIA), the computer program was fist used in 1992 for the Fish Sculpture in Spain.

For drawings to become tangible buildings, the communication of information regarding its construction is of primordial importance. The architectural design through a two dimensional orthogonal projection of space, such as a plan or a section of a building, is suitable for linear architectural objects. However, when the architectural drawing describes a plane that is not flat but curved in two directions for instance, immediately the reading of the architectural information is not suitable with the help of a two dimensional representation. A virtual three-dimensional model facilitates the reading of more complex forms, such as double curved planes. Furthermore, it is possible to extract and communicate geometrical data from the virtual three-dimensional model from the computer to a kind of CNC machine. Consequently, the building information is not only represented as in the case of a two-dimensional drawing but with a virtual model, it is the information.[6]

The means of construction of a building changed with the use of computer numerically controlled machines. During the industrial age, mass production allowed new building technologies to architects of the modern movement. The information age likewise, offers novelties regarding the construction technology for example mass customization as opposed to mass production related to the industrial age. The development of modern architecture relied both on new aesthetics principles and innovations in the domain of technology. The new use of materials such as iron, steel and glass gave new opportunities to an architecture partially restricted until then .

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6 Kolarevic Branko (ed.) “*Architecture in the digital age design and manufacturing*” , Spon Press,New York 2003.

In the 20th century, space seems to acquire a new sense aiming to fulfill the new needs of living in the following of the industrial revolution. Similarly, at the beginning of the information age, technology greatly influenced architecture by offering the digital infrastructure to the construction process.

In the passage from the industrial to the information age many factors influenced architecture. Specifically this paper aims to show how architecture represents the changes regarding the notions of space and time in the 20th century, in relation to the scientific changes in physics and philosophy, the available design tools and building technologies that allowed for a transformation in architectural shapes and forms. What is the architectural space of the four-dimensional continuum in the context of the digital age ?

CULTURAL CONTEXT

20th-century art, science and architecture included, began with new ways of conceiving time and space. Einstein was in a cultural generation of scientists that inherited a Newtonian tradition in physics, all its advances, problems and limitations included. Einstein lived at a turning point of world events, his discovery happened in the context of decisive developments. Major events of early 20th century for example, World War I from 1914 to 1918 or the October revolution in 1917 in Russia. The first flight in 1903 by the Wright bothers, Wilbur (1867-1912) and Orville (1871-1948) and the first assembly-line mass-manufactured car by Henry Ford (1863-1947) in 1912. Bertrand Russel (1872-1970) with Alfred North Whitehead (1861-1947) wrote in 1910-1913 "*Principia Mathematica*" in an attempt to combine mathematical language and logic.[7] (gleick p.178) and Pablo Picasso (1881-1973) introduced the revolutionary art of Cubism .

In 1922 Einstein won the Nobel Prize, James Joyce published "*Ulysses*" known for its narrative fragments and T.S. Eliot published *The Waste Land*. The same year in Paris in May, there was a party for the opening of the ballet "*Renard*", performed by Diaghilev's Ballets Russes, Igor Stravinsky who composed the music was present, so was Picasso who designed the sets, as were Joyce and Proust who was beginning "*Remembrance of Things Past*".

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The art of each o these personalities, represented in an artistic language the sense that space and time were not absolute. Picasso painted "*Les Demoiselles d' Avignon*", famous for introducing a multiplicity of perspectives of an object into a single frame, in 1907.

Figure 1- Pablo Picasso's painting Les Demoiselles d'Avignon (1907)

> " Four-dimensional space replaces Euclidean space first in Cubism. The concept of simultaneity brings forth the coexistence of more than one point of view expressing aesthetic experience in time. Representation of the visual memory of a moving observer is preferred to optical vision in Cubist paintings." [8]

Cubism completely avoids the traditional illusion of depth by means of perspective, it was about

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[8] Gül Kaçmaz Erk and Belkıs Uluoğlu "*Changing Paradigms In Space Theories:Recapturing 20th Century Architectural History",* International Journal of Architectural Research Archnet IJAR, Volume 7 - Issue 1 – March 2013. p12

Figure 2 Dynamism of a dog on a leash Giacommo Balla 1912

the restructuring of space with simultaneous views, however, Futurism was interested in the dissection of time. One of the futurist techniques was to superimpose a series of successive instants in time upon one another in other words to have simultaneous views in time. . A work that symbolizes both cubism and futurism is Marcel Duchamp's Nude Descending a Staircase No.2 (1912).

The Cinematographe invented by the Lumière brothers in 1895 is not only a mere technological invention as it opened the path for a major art of the XX th century, cinema. The 7th art is very much important as it captures movement, as Fuller explains no still image will show that a caterpillar becomes a butterfly or that a butterfly can fly. For Einstein the universe is an aggregation of phenomena that transforms energy events , it is a permanent mutation, its a scenario. Multiple views, multiple instants and movement is involved space shifts from three-dimensional to the space-time continuum.

Figure 3 "Nude descending a staircase" Marcel Duchamps 1912

CONCEPTS OF SPACE AND TIME IN PHYSICS

The notions of Space and Time have changed from a Newtonian definition of these concepts to Einstein's Space-time concept. Profound changes in scientific ideas influence drastically the cultural structure in which they are redefined. They do so by giving new meanings to three basic notions matter, time and space. Even if somehow calculable, these notions are quite abstract, they are identified through philosophical predicates defined differently by different cultures at different times. The shift from Newton's notion of space and time to Einstein's space-time continuum has had a profound impact on our western technological society. The two physicists use different kinds of geometry to explain their theory. The mathematical notion of Space and Time seem to have changed, the geometrical nature of the universe described by Newton is based on three-dimensional Euclidean geometry where as Einstein's view relates to a four-dimensional non-Euclidean geometry.

Similarly, in architecture, the kind of geometry that will be used during the design is influential upon the shaping of the building. During the process of design, architects can use non-Euclidean geometry in order to create shapes resulting from topological or parametric relationships for instance. These shapes are characterized notably by fluidity, complexity, and movement. In contrast, the representative shapes of the modern movement in architecture have mostly on purpose (for aesthetic and ideological reasons) more simple Euclidean relationships related to the Cartesian grid. Continuity, time and movement has been a preoccupation of architecture since the 19th century but it is in the 20th century that time is regarded as the fourth dimension of space.

Geometry is a very important tool in order to describe spatial relationships. The geometry, as spatial coding, is not determinative but influential on the tangible result of the building. Even though the geometry used in the process of design can originate from different conceptual approaches, the build architectural object is always described by three-dimensional Euclidean geometry. Mathematically, shapes can have any sort of geometrical relation, nevertheless physically, a building, as the organization of tangible matter requires the coding of this space as Euclidean therefore three-dimensional. Still, if some type of non-Euclidean geometry is used during the design it will impact its own translation in its Euclidean form, the build architectural object.

Mathematics and physics, thus, have a great impact on architecture by offering different concepts of space. The theory of relativity is based in a four-dimensional non-Euclidean geometry called Riemannian Geometry or Spherical Geometry. The geometry of Riemannian manifolds is key in the theory of relativity and possibly in the architecture of the digital Age.

PRE-RELATIVE PHYSICS: NEWTON AND EUCLIDEAN GEOMETRY

Isaac Newton's (1643 -1727) concepts of space, time, and motion were emblematic in physics from the 17th Century until the 20th Century, when the theory of relativity appeared and started to have an impact. Newton's research expanded over a wide range of domains, from optics to the formulation of the three Newtonian laws of motion, developing differential and integral calculus .In 1687, Newton's “*Philosophae Naturalis Principia Mathematica”* (“*Mathematical Principles of Natural Philosophy”*) was published where he formulates classical mechanics and gravitational theory. His law of gravity is important because through it Newton explains and unites various physical phenomena within a single theory, it states that the force of gravityy (F) between two objects of masses m and M is given by the formula, $F = G\,mM/d^2$ where F is the force in Newtons, m1 and m2 are the masses of the bodies in kilograms, G is the gravitational constant, and d is the distance between the bodies in meters. The law of gravitation supplies the theoretical framework in order to explain Keppler's discovery regarding laws for the motion of the planet and it also explains that a planet's trajectory is elliptical and not circular[9]. A "Scholium" at the beginning of the *Principia*, lays out Newton's concepts on time, space and among other notions.

> *"Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year."*[10]

> *"Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space; such is the dimension of a subterraneous, an aerial, or celestial space, determined by its position in respect of the earth. Absolute and relative space are the same in figure and magnitude; but they do not remain always numerically the same. For if the earth, for instance, moves, a space of our air, which relatively and in respect of the earth remains always the same, will at one time be one part of the absolute space into which the air passes; at another time it will be another part of the same, and so, absolutely understood, it will be continually changed."*[11]

He is considered one of the most important physicists and mathematicians, significantly contributing to classical physics by giving words such as *force, mass, motion* and *time*[12] , not only new meanings but the quantification of those terms as well so they could be used in

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[9] Basset Bruce, Edney Ralph , *"Introducing relativity"*, Gutenberg Press, Malta 2002.

[10] Newton Isaac, Scholium to the Definitions in "*Philosophiae Naturalis Principia Mathematica*", Bk. 1 (1689); trans. Andrew Motte (1729), rev. Florian Cajori, Berkeley: University of California Press, 1934. pp. 6-12.

[11] Newton Isaac *Op.cit.*

[12] Gleick James , "*The Information: A History, a Theory, a Flood*", Fourth Estate Paperback, Great Britain 2012 p.7

mathematical equations thus explaining the use of the adjective “mathematical” in the title of his work *“Mathematical Principles of Natural Philosophy”*. Isaac Newton founded classical mechanics on the view that *space* is distinct from body and that *time* passes uniformly without regard to whether anything happens in the world. For this reason he spoke of *absolute space* and *absolute time*, so as to distinguish these entities from the various ways by which we measure them (which he called *relative spaces* and *relative times*).[13]
Time in Newton's view is a continuum independent from the the continuum of the Euclidean space. In the Newtonian notion of time, time is exact and the same homogeneously in the Universe. *“According to classical mechanics, time is absolute, ie, it is independent of the position and the condition of motion of the system of coordinates.”*[14] So at that period, scientists took for a fact that the Universe is instantaneous because the speed of light was yet to be measured. It's only in the 20th century that the speed of light was calculated, this means that until the 20th century scientists believed when looking at the stars that they were fixed in place that the universe was somehow static. According to Newton's Law immobility is the norm and movement is the exception.[15]

> *“In Newtonian mechanics, space and time [...] play the part of carrier or frame for things that happen in physics, in reference to which events are described by the space co-ordinates and the time. In principle, matter is thought of as consisting of “material points,” the motions of which constitute physical happening [...] If matter were to disappear, space and time alone would remain behind (as a kind of stage for physical happening).”*[16]

Thus, for Newton, Space and Time are absolute and distinctive entities. While Newton believed that the Earth is round he accounted that space is flat. The limited vision of flat spaces comes from the legacy of Euclidean Geometry.[17] The geometry that describes the Newtonian spatial relationships are described in the realm of an Euclidean geometry which is three-dimensional, this means that we need three co-ordinates x,y and z to describe the position of a point. Until recently there was no need to mention the adjective Euclidean when associated with

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[13] Rynasiewicz, Robert, *"Newton's Views on Space, Time, and Motion"*, *The Stanford Encyclopedia of Philosophy* (Summer 2014 Edition), Edward N. Zalta (ed.),
[14] Einstein Albert, *“Relativity, The Special and General Theory”* New York: Pi Press, 2005,(1920), p.62
[15] Snyder Robert,“Buckminster Fuller: scénario pour une autobiographie” Éd.Images modernes, Paris, 2004
[16] Einstein Albert, “Relativity, The Special and General Theory”(1920), New York: Pi Press, 2005 p. 165-166
[17] Basset Bruce, Edney Ralph,*“Introducing relativity”*, Gutenberg Press, Malta 2002.

geometry, as it was implied within the meaning of the word. The Euclidean geometry that describes physical objects in classical physics started around 300 B.C whereas only since the 19 th Century do we refer to a kind of geometry that is Non-Euclidean.

Euclid's “Element”organized a great body of mathematical knowledge within thirteen books. Euclid's method of deductive systematization used propositions based on definitions, axioms, postulates and theorems that created geometrical knowledge for centuries. The four first postulates are evident but the fifth postulate which considers the definition of “parallelism” asserts that :

> *“two lines are parallels, i.e. non-intersecting, if there is a third line that intersects both perpendicularly. The consequence of this postulate in Euclidean Geometry is that through every point there is one and one only line parallel to any other line.*[18]

This fifth postulate by not being considered a postulate of absolute geometries like the four fist ones allowed for the blooming of non-euclidean geometry in which th theory of relativity occurs. The concepts of space and time in classical physics greatly influenced the theory of relativity. Instead of being flat as in Newton's view, space, in the theory of relativity is curved. Space-time is curved probably by any energy in the universe. Newton's first Law states that a body will move along a straight line in space unless a force acts on it. *Einstein modified Newton's Law saying that a body will move along the curve of shortest distance in space-time unless a force acts upon it.*

RELATIVE PHYSICS: EINSTEIN AND NON-EUCLIDEAN GEOMETRY

In 1905 Einstein's “Special Theory of Relativity” is published and in 1916 his work with the title “General Theory of relativity”. Both theories are non Newtonian theories of gravity with spatial relationships being described in a four-dimensional Riemannian geometry of manifolds.[19] By 1907, Einstein’s former teacher and friend, Hermann Minkowski, realized that the special theory of relativity could be best understood in four dimensional space, now known as “Minkowski space-time”, in which time and space are not separate entities but intermingled in four dimensional space-time. The mathematician created a hypothesis of the unity of space and time, to determine the geometric structure of that space–time unity. Minkowski stated that, in the

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[18] Kolarevic Branko (ed)*“Digital Morphogenesis ”in“* Achitecture *in the digital age design and manufacturing”,* Spon Press,New York 2003. p.19

[19] Braidotti Rosi, Pisters Patricia, “*Revisiting normativity with Deleuze”* , New York : Bloomsbury, 2012.

four-dimensional world, one point has four coordinates: three of which are space coordinates defining the event location, with the fourth coordinate defining the time of the event. This four-dimensional space is called an event space or Minkowski space.

Einstein was interested in experiences that proved that light has a speed. In the 1880's, Albert Michelson (1852-1931) and Edward Morley (1838-1923) discovered that the speed of light remains constant regardless of the speed of its point of observation. An observer moving does not perceive light moving faster than an observer standing still. In the 20th century, light has a calculable speed and it is constant. It takes light 8 minutes to come from the sun to the earth and two years and a half to come from the closest star. To look at the stars is to watch an asynchronous spectacle of light, a star could be thirty thousand years old next to it could be three thousand years old star and some other star may possibly not exist anymore. In Newtonian physics, space and time are absolute and the speed of light is relative, in relative physics space and time are relative and the speed of light is absolute.

The measure of the speed of light is very important for many reasons, one that relates to architecture is that since 1983 it defines the unit of length, the metre. According to the BIPM[20], the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards, defines : *"The metre is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second."*[21] The previous definition of the metre was a tangible example locally kept in France and served as a common reference for what we consider to be 100 cm. Hence, the new definition of the metre, by relating to the speed of light and not a physical prototype, delocalizes the metre.

Einstein explored the idea that the speed of light is constant whereas time is not. From 1902 to 1909 Einstein worked at the Swiss Patent office in Berne. Fuller (1895-1983) postulates that Einstein by working on innovations regarding the measure of time therefor evaluating these inventions, started to think about the question of time. As scientists came through Einstein's office during his work at the Swiss Patent office, they each explained that the precision of a clock is not absolute and how the process they each proposed gave a more accurate calculation of time. Fuller believes that this is how Einstein started to think that time is not absolute .

There are two views of the fourth dimension, one in the branch of Physics and one in Mathematics. Firstly in Mathematics four dimensions refer to four Euclidean planes, secondly in physics four dimensions refer to three dimensions of space and one dimension of time.

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20 Bureau International des Poids et Mesures (in French), responsible for the international system of units.

21 http://www.bipm.org/en/publications/si-brochure/metre.html

The mathematical spatial fourth dimension is something that we can only imagine, not perceive, we can describe it mathematically but we can't perceive it physically. In order to understand this we need to imagine a plane perpendicular to the three planes of the three dimensions that the human senses perceive, width, height and length. In a world described with Riemennian geometry, Minkowsky elaborated a mathematical theory which stipulates that if isolated "very small" pieces of space have properties of euclidean geometry. Very small domain (environment) affects through analytic continuation the whole of Riemann surface, or analytic manifold .

Minkowsky knowing that a four-dimensional geometry falls outside of human senses, imagined a euclidean plane tangent at the point of the observer in the 4D spatial geometry, the pseudo Euclidean space Minkowsky. Since this space is three-dimensional, it is observable by human senses, phenomenons of four-dimensional space-time are projected on a three-dimensional space. Human perception can't observe four-dimensional phenomenons but can observe the projection of these phenomenas on the pseudo euclidean space, their images. So what we observe through human senses is not reality but a distorted image of this reality projected on an euclidean plan that deforms the phenomenas.

> *"Similarly, the world of physical phenomena which was briefly called "world" by Minkowski is naturally four-dimensional in the space-time sense. For it is composed of individual events, each of which is described by four numbers, namely, three space co-ordinates x, y, z and a time co-ordinate, the time-value t. [...] That we have not been accustomed to regard the world in this sense as a four-dimensional continuum is due to the fact that in physics, before the advent of the theory of relativity, time played a different and more independent role, as compared with the space co-ordinates. It is for this reason that we have been in the habit of treating time as an independent continuum."*

Thus, Einstein through his theory of relativity unifies Newton's absolute and distinct Space and Time entities as one notion called Space-Time. The theory of relativity is based in a four-dimensional Riemannian Geometry. The geometry of the Riemannian manifold is fundamental in the theory of relativity.

The German mathematician Bernhard Riemann (1826-1866) based his studies on curvatures using differential geometry to define and calculate curvature.[22] The "elliptic geometry" is concerned with the study of surfaces or spaces with variable curvature. Riemann's geometry is considered a non-euclidean geometry because the parallel lines defined in the Fifth

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[22] Henderson, Linda Dalrymple, "*The Fourth Dimension and Non-Euclidean Geometry in Modern Art*." Princeton, NJ: Princeton University Press, 1983.p.5.

Postulate of Euclid do not exist in Riemannian geometry. Euclid's second postulate is that a straight line of finite length can be extended continuously without bounds. However, in Riemannian geometry, with space as a spherical surface, lines are defined as circles intersecting at the poles, subsequently lines are unbounded but still of finite length. Among many differences between Euclidean Geometry and Riemannian Geometry is for example the fact that in Euclidean geometry the sum of the angles in a triangle is 180 degrees, distinctively in elliptical geometry it is greater than 180 degrees.

In1873, he introduced for the first time the concept of the Riemannian manifold in his work *"On the hypothesis which Lie at the basis of Geometry"("Ueber die Hypothesen, welche der Geometrie zu Grunde liegen").*[23] A Riemannian manifold is defined as :

> *"a conglomerate of continuously connected (local spaces), each of which can be mapped by a (flat) Euclidean, or Cartesian, coordinate map and be treated accordingly (and thus can also be given geometry), without allowing for a global Euclidean structure for the whole, except in the limited case of an Euclidean homogeneous (flat) space itself. More precisely, every point of such a space has a small "neighborhood" (also used as the technical mathematical term) that can be treated as Euclidean, while the manifold as a whole in general cannot."*[24]

As Maurin explains, a Riemann space is firstly locally Euclidean, secondly every sub-manifold of Euclidean space is equipped with Riemann natural metric and thirdly it is isometrically embedded in a certain Euclidean space of n dimensions. Meaning that every Riemannian space is a sub-manifold of an Euclidean space with potentially more than three dimensions. "'The geometry of space offered by Riemann was not just an extension of Gauss's differential geometry. It reconsidered the whole approach to the study of space.'[25]And we could add that this new way of posing spatial problems would, a few decades later in the hands of Einstein and others, completely alter the way physicists approached the question of space (or more exactly, of space-time)"[26]

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23 Plotnitsky Arkady, *"Manifolds on the concepts of space in Riemann and Deleuze"* in " *Virtual Mathematics: the logic of difference"*, ed. Simon B. Duffy, Manchester: Clinamen Press, 2006. http://web.ics.purdue.edu/~plotnits/PDFs/Manifolds.pdf

24 Plotnitsky Arkady, *"The Spacetimes of Nympheas: Matter and Multiplicity Einstein, Monnet and Deleuze and Guattari"* in "*Revisiting normativity with Deleuze"* ,Braidotti Rosi, Pisters Patricia (eds.), New York : Bloomsbury, 2012. p 39

25 Kline Morris, *"Mathematical Thought from Ancient to Modern Times"*, Vol. 3,New York: Oxford University Press, 1972. p. 890

26 DeLanda Manuel, *"Intensive Science & Virtual Philosophy",* Bloomsbury Revelations, 2013 p.12

figure 4 - crumpled paper ball symbolizing the Riemanian manifold

The Riemenian manifold is a mathematical concept of space at the center of the theory of relativity and is also a key concept in the philosophical work of French philosophers Henri Bergson and Gilles Deleuze .

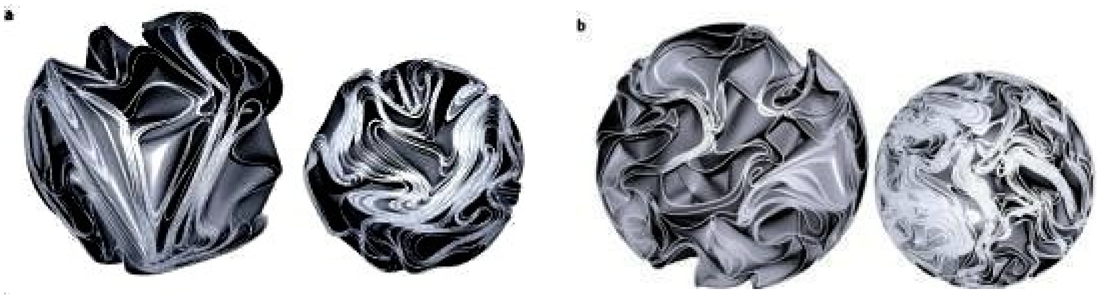

Figure 5: Intersections of crumpled sheets symbolizing the hidden dimensions of the Riemanian manifold

“Einstein, my upset stomach hates your theory [of General Relativity]—it almost hates you yourself! How am I to' provide for my students? What am I to answer to the philosophers?!!”-

- Paul Ehrenfest

PHILOSOPHY OF TIME IN THE 20TH CENTURY

The underlying "metaphysics" of time has profoundly changed, and it is this metaphysics that constitutes the object of Deleuze's philosophy. "Bergson says that science has not found its metaphysics, the metaphysics it needs," Deleuze once wrote, "It is this metaphysics that interests me" [27]

BERGSON

French philosopher Henri Bergson (1859–1941) influenced many thinkers, Gilles Deleuze in 1966, with his book "*Bergsonism*" sparked a renewal of interest in Bergson's work. The concept of Bergson which Deleuze seems to be the most fond of is the one of multiplicity which tries to unify the opposite notions of *heterogeneity* and *continuity.* Deleuze argues that the notion of multiplicity forms a central part of Bergson's critique of the dialectical method. Bergson's theory of multiplicities distinguishes between two types of multiplicity: continuous multiplicities and discrete multiplicities.

> *"The word multiplicity is not there as a vague noun corresponding to the well known notion of the Multiple in general. In fact for Bergson it not a question of opposing the Multiple to the One but, on the contrary of distinguishing two types of multiplicity. Now this problem goes back to a scholar genius G.B.R Riemann, a physicist and mathematician. Riemann defined as "multiplicities" those things that could be determined in terms of their dimensions or their independent variables. He distinguished discrete multiplicities and continuous multiplicities. The former contain the principle of their own metric (the measure of one of their parts being given by the number of elements they contain). The latter found a metrical principle in something else, even if only in phenomena unfolding in them or in the forces acting in them. It is clear that Bergson, as a philosopher, was well aware of Riemann's general problems. Not only his interest in mathematics points toward this, but, more specifically, Duration and simultaneity is a book in which Bergson opposes his own doctrine to the theory of Relativity, which is directly dependent on Riemann."*[28]

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27 Villani, Arnaud. " *La guêpe et l'orchidée: Essai sur Gilles Deleuze".* Paris: Éditions Belin.1999 p.130
28 Deleuze Gilles, *"Bergsonism"* (1966), translated by Hugh Tomlinson and Barbara Habberjam, New York: Zone Books,1991.

In 1922, Bergson wrote, *"Duration and Simultaneity With Respect To Einstein's Theory"* (*Durée et Simultaneité, À propos de la théorie d'Einstein*), to explore how his concept of duration corresponds with Einstein's special theory of relativity.
Bergson focused on updating the philosophical concept of Time similarly to the way relativity in physics remodeled the views of physical phenomenons from the Newtonian model in 1905.
In 1922, Einstein visited Paris, during a meeting of the French Philosophical society in which he had a small encounter with Bergson. Einstein and Bergson had a public disagreement over the notion of Time related to the theory of relativity. Even though Bergson had great respect and admiration for the physicists he opposed against Einstein' view of simultaneity. Einstein replied to Bergson's criticism :

> *"The question is therefore posed as follows: is the time of the philosopher the same as that of the physicist? The time of the philosopher is both physical and psychological at once; now, physical time can be derived from consciousness. Originally individuals have the notion of simultaneity of perception; they can hence understand each other and agree about certain things they perceive; this is a first step towards objective reality. But there are objective events independent of individuals, and from the simultaneity of perceptions one passes to that of events themselves. In fact, that simultaneity led for a long time to no contradiction [is] due to the high propagational velocity of light. The concept of simultaneity therefore passed from perceptions to objects. To deduce a temporal order in events from this is but a short step, and instinct accomplished it. But nothing in our minds permits us to conclude to the simultaneity of events, for the latter are only mental constructions, logical beings. Hence there is no philosophers time; there is only a psychological time different from that of the physicist."*[29]

The opinions about the debate are mitigated, some people say that Bergson didn't understand the theory of relativity, others that Bergson understood the theory and discussed a very subtle point of the theory.[30] Bergson wants to investigate the idea of a unique and universal time in the theory of relativity among its multiple flow of times but is opposed on the view of simultaneity.[31] Eventually, Einstein's opinion of simultaneity was verified, it is Einstein's view of time and simultaneity that prevailed and dominated the general opinion of the 20th-century.

In 1896, Bergson wrote *"Matter and memory"*, he rethinks geometric and spatio-temporal relations through the notion of duration and critiques the scientific Cartesian method. Bergson in his philosophical works highlighted the difference between dynamic time as

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29 Gunter, P. A. Y. *"Bergson and the Evolution of Physics"*.University of Tennessee Press.1969 p.133
30 Guerlac Suzanne, *"Thinking in Time, An Introduction to Henri Bergson",* Ithaca United states:Cornell University Press, 2006.. p.10
31 For further information see ...

experienced by a biological body and measurable static time. An objective static time and a subjective human experience of time. Duration, in Bergson's view, is when time perception is related to the subject (dynamic), it is composed of moments sequentially ordered in past, present and future in an irreversible manner because of our memory. Dynamic time has a direction and is an accumulations of directions. In a very uneven way, time in the past and in the future are two different notions with a very imbalanced and chaotic relation. Time in the past is fixed (experiences on memory) and the future is indefinite because of the multiple potentials of the experienced event before its actualizations. Therefore, the notion of duration includes an incessant creation of possibilities.[32] Duration subsequently creates a topological geometric method in opposition to the Cartesian scientific method. For Bergson, the perception of the world is the reflection of the possibilities of bodily action as he concludes, perception is virtual action.[33] The French philosopher criticized Descartes scientific method because it relies on mechanical relations. Bergson argues that followers of the Cartesian method are confused about the structure of movement between the parts and the whole because of the restricted view of the geometric relations they use. However, homogeneous space and time are required in order for change to be actualized because they provide bridges between the virtual and the the physical act. [34]Nevertheless, when movement is considered within Riemann's topology Bergson emphasizes that we can examine heterogeneous space-time: " a moving continuity is given to us, in which everything changes and yet remains: why then do we dissociate the two terms, permanence and change, and then represent permanence by bodies and change by homogeneous movements in space?"[35] Static quantitative time creates homogeneous spaces which we need in order to actualize the the virtual duration of memory and dynamic qualitative time defines heterogeneous spaces because they promote internal dynamical relations between geometry space and time through perception, duration and memory. "*Matter and Memory*", defines a qualitative notion of time, with the human body as an instrument of measure of duration in relation to *virtual action,* and describes the relationship of the body with the notion of duration as topological relationships. Hence, Bergson proposes the radicalization of the nature of space in relation to time and geometry at the very end of the 19th century.

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32 Rahim Ali, *"Designing and manufacturing performative architecture"* in " Achitecture *in the digital age design and manufacturing"Kolarevic Branko (ed),* Spon Press,New York 2003 p. 284

33 Robbins, S. E. "Special Relativity and Perception: The Singular Time of Psychology & Physics",in Journal of Consciousness Exploration & Research | Vol. 1 | Issue 5 | Pages 529-559 | July 2010. p.11

34 Rawes Peg, "*Space,geometry and aesthetics,Through Kant and towards Deleuze",* U.K: Palgrave Macmillan, 2008. p137

35 Bergson Henri, *"Matter and Memory"* (1896),translated by Nancy Margaret Paul and W. Scott Palmer, New York: Zone Books, 1991 p. 197

DELEUZE

Deleuze acquires the concept of multiplicity from Riemann and Bergson and develops it in many of his works and in a variety of ways. In general, he also rejects the “One-Many” dialectic and proposes multiplicity instead. Just as Riemann created a non-Euclidean concept of space as an *n*-dimensional manifold with no pre-given metric, Deleuze formulates a non-chronological concept of time as an *n*-dimensional and non-metrical manifold defined by "a formal network of processes" [36].

‘Multiplicity must not designate a combination of the many and the one, but rather an organization belonging to the many as such, which has no need whatsoever of unity in order to form a system.’[37] As Manuel Delanda tells us, the term ‘multiplicity’ is closely related to that of ‘manifold’, a term which designates a geometrical space with certain characteristic properties. The term ‘manifold’ does not belong to the analytical geometry of Descartes (1596–1650) but to the differential geometry of Friedrich Gauss (1777-1855) and Bernhard Riemann.[38] Gauss proving with his theory “*Theorema Egregium”* that the spherical property is an intrinsic property. Resulting in the fact that there is no way to illustrate a three dimensional sphere on a two-dimensional plan and maintain unaltered sizes such as angles, lengths or areas.[39] Then, he developed the concept that a two-dimensional surface is a space in itself, which was later further developed by Riemann (his student) on another level the N-dimensional surfaces or spaces. The term manifold mathematically is firstly referred to as N-dimensional curved structures, denominated solely through their intrinsic properties. Following the Riemannian mathematical model, a Deleuzian multiplicity is principally characterized by firstly, a variable number of dimensions and secondly the omission of an additional dimension imposing an extrinsic system of coordinates. As follows, unity would then be extrinsically defined as opposed to “intrinsically defined, without external reference or recourse to a uniform space in which it would be submerged"[40]

Some geometries define spaces according to lengths, distances or areas for example, these kind of geometries like the Euclidean Geometry create metric spaces. On the other hand spaces of another kind exist such as dynamic or topological spaces where metric distances are not much help. A topological space can be stretched without altering the nature of the neighborhoods that

36 Williams James, “*Gilles Deleuze's Philosophy of Time: A Critical Introduction and Guide*”, Edinburgh University Press, 2011
37 Deleuze Gilles, *“Difference and Repetition”*, New York :Columbia University Press, 1994,, p. 182
38 *DeLanda Manuel, “Intensive Science & Virtual Philosophy”,* Bloomsbury Revelations, 2013 p.10
39 A characteristic example is that you can't peel an orange or an egg in one piece without it ripping, twisting or folding. We can deduce from this theory that a map of the world always has some characteristics unaltered while others are deformed.
40 Deleuze Gilles, *“Difference and Repetition”*, New York :Columbia University Press, 1994, p. 183.

define it. A dynamic object can move in different ways , the ways the object can change can be defined and then those ways of changing can be interrelated to each other through differential calculus.

In the Deleuzian ontology there is an essential difference between metric and non metric spaces. Suppose Deleuze's ontology is considered as different subdivisions for instance the notions of singularities, difference and multiplicity . We then observe that these subdivisions are all based on a differential value, they have no presupposition as self identities in contrast they are defined by differences relative to their internal composition. As a result we can conclude that the actualization of these categories in applicable concepts implies their differentiation and under those circumstances create novelty.[41] Deleuze's own inspirations as well as influences, go beyond philosophy often to reach a multi disciplinary context. He was curious and inspired by many disciplines and reciprocally he influenced various domains of culture for example mathematics, art or geography to name a few. His work is substantially cited and his concepts often utilized by researchers in architecture, urban studies and film studies amongst other fields. As far as architects are concerned many were influenced in various ways.

After writing on his own Deleuze later writes with Felix Guattari about the concept of multiplicity. Together they continue to borrow the mathematical and physical notion of space-time in the theory of relativity such as the Riemannian manifold but translate its usage for the purpose of a philosophical concept of multiplicity.

THEORY OF RELATIVITY & ARCHITECTURE

Einstein's theory is quite significant in the philosophical concept of time of the 20th century. Since many architects of the end of the 20th-century are influenced by the theoretical works of Deleuze, it seems possible that architects may have encountered the theory of relativity indirectly.

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[41] Deleuze doesn't choose to express himself with notions such as possible or real but prefers virtual and actual probably because the real can resemble the possible whereas the actual differs from the virtual.

DELEUZE'S INFLUENCE ON ARCHITECTURE

The traduction of the works of Deleuze alone and of his tandem with Guattari spread their influences outside of France and of Europe. French architect Jean Nouvel has mentioned the same remark about the work of Deleuze and Guattari three times, citing from Adams :

> *"After Foucault I found much of interest --as well as some distress elements -- in the books of Deleuze and Guattari and especially in their most recent publication What is Philosophy? For they explained things that have been familiar to me for ten years, but in a far more precise, advanced, and intelligent way. But in the end, they were speaking of concept, percept, and affect, while I was talking about concept, sensation, emotion. The idea that the notion of concept is reserved for philosophy led me to ask myself whether I had been guilty of misusing it. And then, when I saw there 'is no simple concept. Every concept has a number of components . . . it is a multiplicity'; when I read that a concept 'has an irregular outline defined by the number of its components, that every concept has a history, that every concept has a future, that each concept will be considered as the point of coincidence and condensation of its own components,' I felt that I understood that this could equally well be applied to a purely architectural concept. That there could be a correspondence between the world of philosophy and the world of architecture."* [42]

In Europe the influence of Deleuze on architecture started notably early in the Netherlands. According to Gijs Wallis de Vries, It seems that as soon as 1972, Dutch theorists started to get acquainted with Deleuze through the translation of his work "*Proust and Signs*". Ben van Berkel and Rem Koolhaas have partly been inspired by concepts of Deleuze and Guattari. It is also worth mentioning Joost Meuwissen who started a journal *Wiederhall* with articles related to the work of the French theorists. [43]

In 1993, Gilles Deleuze's book *"The fold: Leibniz and the baroque"* was translated in English and began to influence North American architects, remarkably Peter Eisenmann and Greg Lynn. The same year, an edition of the periodical Architectural Design themed "Folding in Architecture", was edited by Gregg Lynn, the issue presents an extract from The Fold (Deleuze 1993). In this case, Eisenman is linked with Deleuze and Guattari on account of an illustration of the concept model of Eisenman's Emory Center along the side of the text's passage.

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[42] Adams Tim, *Diagrams of Interface, or, Deleuze and Gauttari's Legacy to Architects* Deleuze Symposium,University of Western Australia, 1996 p.12

[43] *Ibid*, p.16

Deleuze's view of Leibniz diffused a new course of thought according to Lynn, that of the "integration of differences within a continuous yet heterogeneous system."[44] In 1686 Leibniz, created with differential calculus a method that could calculate and analyse the rates of change of curves and figures. Differential calculus soon had practical applications relating to physics and engineering for example. To illustrate, differentiation, mathematically remodeled the formulation of physical phenomena of movement as well as the delineation of curves for the design of ships and bridge. Philosophically, Leibniz's method allows the concept of continuous difference as a continuous evolution of form. According to Deleuze, Leibniz affiliates difference with the notion of a unified continuity as opposed to separate entities , this affiliation when in process is what Deleuze termed *Folding*. Lynn interprets this new logic of curvilinearity in architectural design as the replacement of fixed coordinates by dynamic relations . In 1993, in his essay on "Architectural Curvilinearity", proposes a design strategy that shifts away from Euclidean geometry in Cartesian space to use instead topological conception of shapes continuous curves and surfaces as formal expressions.

This new mathematical geometry influenced how we design architecture and describe space in geometrical codes. It seems that there are two ways of expressing this change in architecture, by translating this logic into visually curved architectural forms or by implementing the new logic within the design process as an intellectual tool for instance which doesn't necessarily express curvilinearity in the architectural object.

In the early 1990's Eisenman's architecture is characterized by triangulation, superficially nothing expresses morphologically the notion of the curvilinearity often associated with the Fold or the mathematical and philosophical concept of differential calculus, however, they are at the center of Eisenman's design process :

[44] Greg Lynn, *Folding , in Folding in Architecture: guest edited by Greg Lynn,* Architectural design, vol 63, 1993 p.8

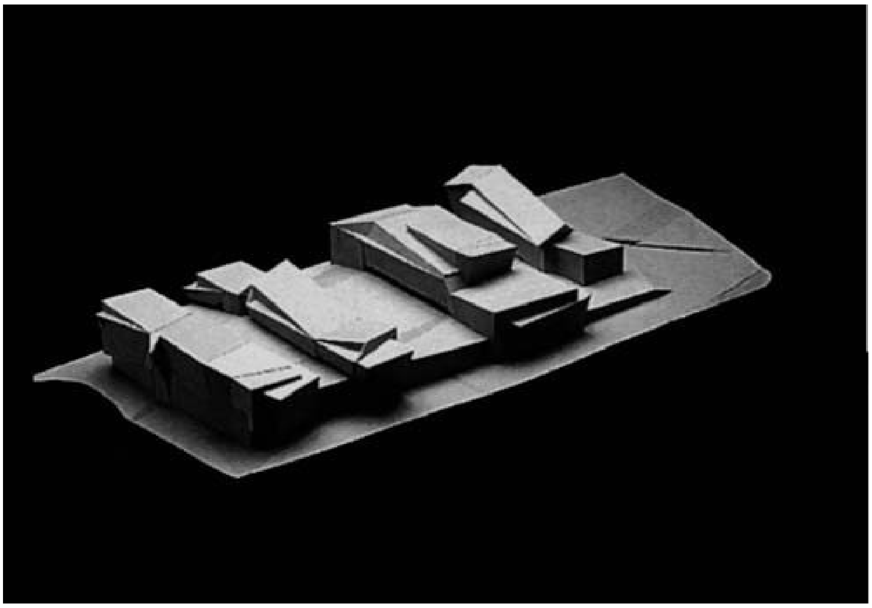

Figure 6: Peter Eisenman: Model of the Emory University Center of the Arts, Atlanta 1991–1993, Folding bars

“Leibniz turned his back on Cartesian rationalism, on the notion of effective space and argued that in the labyrinth of the continuous the smallest element is not the point but the fold’. If this idea is taken into architecture it produces the following argument. Traditionally, architecture is conceptualized as Cartesian space, as a series of point grids. [...] In mathematical studies of variation, the notion of object is changed. This new object is for Deleuze no longer concerned with the framing of space, but rather a temporal modulation that implies a continual variation of matter. The continual variation is characterized through the agency of the fold: ‘no longer is an object characterized by an essential form.’ He calls this form of an object ‘object event.’”[45]

Additionally, Eisenman expresses the fold in terms of topological relations:

“A folded surface maps relationships without recourse to size or distance; it is conceptualized in the difference between a topological and a Euclidean surface. A topological surface is a condition of mapping without the necessary definition of distance. And without the definition of distance there is another kind of time, one of a nomadic relationship of points. These points are no longer fixed by X, Y, Z co-ordinates; they may be called x, y, and z but they no longer have a fixed spatial place. In this sense they are without place, they are placeless on the topological ground. [...] Here the topological event, the dissolution of figure and ground into a continuum, resides physically in the fold; no longer in the point or the grid.”[46]

45 *Eisenman Peter , “Folding in Time: the singularity of Rebstock”,* New York D: Columbia documents of architecture and theory, volume II, 1993. p.24

46 *Eisenman Peter, op.cit.,* p.25

In 1986, Deleuze and Guattari affected some of Japan's Architects with the translation of *Anti-Oedipus* in Japanese. Nippon architecture embraced a variety of the French philosophers concepts, for example Shin Takamatsu engaged in his design process notions of “machinic desiring”. Takamatsu encountered Deleuze and Guattari, Guattari even interviewd the architect for an article in Japanese journal Toshi. Other Japanese architects worth mentioning who took inspiration from Deleuze and Guattari are Todao Ando relating to the term of assemblage, Toyo Ito regarding the concept of nomadism and Kazuyo Sejima in accordance to the notion of smooth space.

These architects whether French, Dutch, North American or Japanese demonstrate a sample of the influence of the philosophical works of Deleuze and Guattari upon architecture. Common denominator in all of these architects is the new conceptual approach of space, a new cognitive framework of space affiliated with time. As Eisenman explains “*Where the specificity of the grid referred to place, the singularity of the fold refers to time and its infinite variations*”[47]. Since Deleuze's work is heavely inspired and by the new notion of time, we can assume that the architects mentioned in the sample are influenced indirectly through his various concepts.

EINSTEIN AND ARCHITECTS

On the other hand, some architects were directly influenced by personal meetings with Einstein such as Le Corbusier, Franck Lloyd Wright, Buckminster Fuller. Einstein's reputation gained him a following among architects who intended to transform architecture and design.

LE CORBUSIER

In 1945, Le Corbusier (Charles-Edouard Jeanneret) (1887-1965) finalized *the Modulor* after twenty years of research on proportion, and which earned him when still a student, his doctorate degree in philosophy and mathematics from the University of Zürich. Le Corbusier's use of the golden ratio in his Modulor system is intended for the scale of architectural proportion. In addition to the golden ratio, Le Corbusier based the system on human measurements, Fibonacci numbers, and the double unit. His measuring system which uses the proportions of the human body to improve the appearance and function of architecture in the tradition of Vitruvius, Leonardo da Vinci's, Leon Battista Alberti amongst others. In 1946, Le Corbusier met Einstein at the university of Princeton and talked to him about “*the Modulor*”. The same evening, Le Corbusier tells us, that Einstein wrote in a letter about “*the Modulor*” :

47 Eisenman, *“Architect-designed Birdhouses”,* A+U:275 ,August ,1993. p.20

> *"It is a scale of proportions which makes the bad difficult and the good easy".He goes on about their meeting : " I had the pleasure of discussing the modulor at some length with professor Albert Einstein at Princeton. I was then passing through a period of great uncertainty and stress; I expressed myself badly, I explained the Modulor badly, I got bogged down in the morass of 'cause and effect'... At one point, Einstein took a pencil and began to calculate. Stupidly, I interrupted him, the conversation turned to other things, the calculation remained unfinished. The friend who had brought me was in the depths of despair."*[48]

FRANK LLOYD WRIGHT

Frank Lloyd Wright (1867-1959) also met with the physicist prior to Le Corbusier in in 1931. Even though they only met in person once, Einstein had the opportunity to experience three of Wright's building, La Miniatura in 1931, the Imperial Hotel in Tokyo in 1922 and Edgar J. Kaufmann's weekend house in rural Pennsylvania, better known as "Falling water" in 1939. Frank Lloyd Wright focuses on organic space with five integrities as he describes in The Natural House, firstly the unity of the interior and exterior, and the house as a whole accompanied of various characteristics the destruction of the box, the wall as a screen, the union of form and function as one for example. Secondly what makes unity and integration possible is glass as a new material, thirdly, continuity expressed as plasticity, continuous movement and flow of space to name a few. Fourthly, the natural use of materials and finally ornament as the expression of inner rhythm of form. The architect send a copy of his book *Modern Architecture* (based on his 1930 Princeton University Kahn Lectures) to Albert Einstein with the inscription : "To the Supreme Scientist Albert Einstein from Frank Lloyd Wright in remembrance of an hour together."[49]

BUCKMINSTER FULLER

Buckminster Fuller (1895-1983) started to write his book "*Nine chains to the moon*" in 1933 , he asked permission from Einstein's editor to cite some parts of the Einstein's work, which they agreed to. Fuller explains his interpretation of Einstein' work in three different chapters based in general from Einstein's cosmical views and some facts Fuller knew about his life. The first chapter is about Einstein's philosophy. Secondly , Fuller goes on to add that in general time is needed when a major scientific discovery is made for the academy of science to acknowledge

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[48] **Le Corbusier,** *The Modulor: A Harmonious Measure to the Human Scale Universally Applicable to Architecture and Mechanics*. de Francia, P and Bostock, A, London: Faber & Faber,1956. p58

[49] Milton Cameron, *Albert Einstein, Frank Lloyd Wright, Le Corbusier, and the Future of the American City,* Institute for advanced studies, Spring issue 2014 https://www.ias.edu/ias-letter/cameron-einstein Last accessed in February 2015

and approve the discovery. It takes even more time to find it into school books and for the new knowledge to influence how students think and eventually create a new intellectual environment. Then, people think with a new manner, inventions are created for example new technologies that would use electromagnetism and would use Einstein's scientific advance that matter is energy. These new technologies would alter the environment of society, which in turn influence social behaviors. Fuller was persuaded that Einstein's relativity which was based on the speed of light would be "the catalyst of a chain reaction that would eventually change our every day lives."[50] Fuller explains that this is the reason that the third chapter dedicated to Einstein is called : "E=mc2=Mrs. Murphy's Horse Power." The third chapter is Fuller's attempt to depict world behavior based on his assumption of how humanity would behave in accord to Einstein's philosophy. At that time Einstein's theory was not verified and Fuller predicating that it would, thought about how it would affect society through practical applications. Buckminster Fuller gathered with the author of the theory of relativity in 1936 and commented on Fuller's interpretation. In the 1960's, Fuller wrote a poem about Einstein, it was published in Saturday Review :

Song of the Dead And the Quick

Newton was a noun
And Einstein is a verb
Einstein's norm makes Newton's norm.
Instant Universe,
Absurd.
"A body persists
In a state of rest
Or---
Except as affected---"
Thus gravestones are erected!

"Non-simultaneous, physical universe
Is Energy; and
Energy equals mass

[50] "Le catalyseur d'une reaction en chaine qui finirait par modifier notre univers quotidien" tramslation Katerina Konstantopoulos. ????

Times the second power
Of the speed of light"
No exceptions!
Fission verified Einstein's hypothesis
Change is normal
Thank you, Albert![51]

It seems that some Architects associated themselves with Einstein had various reasons. Some certainly wanted to gain some sort of additional intellectual credibility, associating a positive connotation to their own work or acted as catalysts for the development of the translation of the paradigm shift within architectural design.

ARCHITECTURE IN THE DIGITAL AGE

The technological society is slowly overturned by inventions and discoveries regarding the communication of information. The architectural scene is influenced by the information Age in many ways in relation to design, architectural representation as well as construction. These processes enhanced with digital means free architects from restrictions and the construction limitations decreases. The theory of information coupled with computer science and the advances in robotics, transformed architecture amongst other socioeconomic structures.
After the industrial age, the information age had many repercussions correlated to various sciences as well as architecture, biology and physics for instance.
Transitioning towards a computer based media, architecture is profoundly affected in connection with the design, its representation and its translation in physical reality, the construction of the building . Architectural design practice, altered in the light of developments in mathematics and geometry, was redefined once more with the introduction of computational design strategies and tools.

“To start thinking of an “informational” architecture, we have to look inside the scientific paradigms of information technology.”[52]

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[51] Buckminster Fuller, “*What I Have Learned VIII, How Little I Know*”, The Saturday Review, pp. 29-31, November 12 1966.

[52] Saggio Antonino, *“Other Challenges”* in “*Architecture in the digital age design and manufacturing*” , Spon Press,New York 2003. p.335

INFORMATION THEORY

"What we call the past is build on bits"

-John Archibald Wheeler.

1948 is an important year in the domain of electronics with two major developments, one regarding hardware and the other regarding theory. That year the invention of a very small electronic semiconductor is announced by Bell Telephone Laboratories. John R. Pierce (1910-2002) called it a transistor (a combination of varistor and transconductance). The same year Claude Shannon (1916-2001) publishes *"A mathematical theory of Information".* Shannon's work creates a bridge between Mathematics and electricity by using the logic of Boolean Algebra. He chooses the word *'bit'* as a fundamental unit to quantify information. By creating a determinate measure for information Shannon began a theory which eventually led to fax machines, computers and cyberspace. Information processing gradually became a problem of storing and retrieving data. Many people argue that the information age is the successor of the steam age. Scientific disciplines were greatly influenced by this technological and cultural shift. Biology for example became an information science observing messages and codes through genetics. Genes transfer and communicate information, D.N.A is the "quintessential information molecule, the most advanced message processor at the cellular level- an alphabet and a code, 6 billion bits to form a human being"[53] . The information Age also had repercussions on the science of Physics. After World War II physicists were mostly keen on two events, the splitting of the atom and the control of nuclear energy. Then the 'bit' became a different kind of particle maybe even more fundamental than matter. It is now suggested that the 'bit' is an "irreducible kernel and that information forms the very core of existence".

John Archibald Wheeler (1911-2008) bridged the physics of the 20th and 21st century by stating "It from Bit", "every it – every particle, every field of force, even the space-time continuum itself" rises from information. Gleick wonders when photons and electrons and other particles interact, what are they really doing? They exchange bits, transmit quantum states and process information. The laws of physics become an algorithm that analyses the universe as an information processor, physics seems to express partly its laws in the language of information for example according to wheeler the bit count of the cosmos is ten raised to a very large power. Basic information technology is the alphabet for example, it is only lately that the radio, the telephone or the computer innovated the way information was saved, manipulated or

[53] Gleick James , "*The Information: A History, a Theory, a Flood*", U.K: Fourth Estate Paperback, 2012. p.8

communicated. Each new information technology changes how we store and transmit data. With the printing press came along new ways of organizing knowledge for example dictionaries or encyclopedias. The theory of information began as a bridge between mathematics and electricity resulting in the evolution of computer science and robotics.

HAND OPERATED TOOLS & 2D DRAWINGS

Technology as well as the economical and political context that frames a building, are very important factors that have consequences upon architectural shapes concerning their design and as on the resulted forms regarding their construction. When profit is the absolute value, architecture undergoes morphological consequences. As Mitchell states there is an economy of architectural shapes and forms. When confronted with tight schedules, deadlines and limited materials, some designs are easier to draw and some forms are quicker and cheaper to build than others.

For many centuries staple design tools for architectural drawing were the straightedge ruler, the divider and the compass, these along Euclidean geometry, described spatial relationships with two dimensional plans and sections. These manually driven design tools together with the tradition of the Cartesian grid, established a hegemonic economy of shapes consisting of lines, circles, triangles including parallel and perpendicular planes.

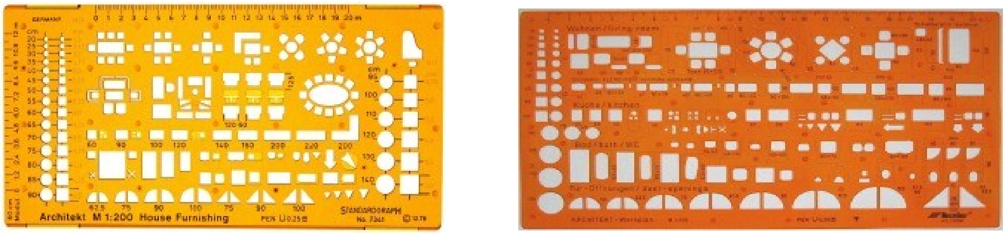

Figure 7. Metric Scale Architectural Drawing Template Stencil

However, all economies are influenced by technological innovations. When see-through paper was available, architects were easily inclined to work with transposition, rotation, mirroring and make copies of design adding various transformations because the thinner paper allowed them to read simultaneously the drawing underneath. Succeeding, was paper with a millimeter grid facilitating the design of modular components, then came the possibility of photography and later on the photocopy machine diminished significantly the cost and time needed to change the scale of a drawing. [54]

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[54] Mitchell W. in the preface of Terzidis Kostas , "*Expressive Form : A conceptual approach to computational design*", London New York; Spon Press , 2003.

Figure 8. Villa Mairea, in noormarkku Finland , 1938 -1939 Alvar Aalto

Figure 9. Eames House, Case Study House No. 8 Pacific Palisades, California 1949 Charles and Ray Eames

Figure 10. Glass House New Canaan, Connecticut 1949 Philip Johnson

Figure 11. Farnsworth House, Plano, Illinois 1951 Ludwig Mies van der Rohe

> *"Since the importation and absorption of perspective by architectural space in the 15th century, architecture has been dominated by the mechanics of vision. Thus, architecture assumes sight as being preeminent and also in some way natural to its own process. It is precisely this traditional concept of sight that electronic architecture questions. The tradition of planometric projection in architecture persisted unchallenged because it allowed the projection and hence, the understanding of a three dimensional space in two dimensions."*[55]

The computer is an important new tool for digital design, on the other hand like any tool its relevance depends in the purpose of its use. We can observe two general interpretations of the role of the computer regarding digital design. The first one considers the computer as an advanced tool, which offers speed and control to the design. In this case the computer is used as a graphical representational tool. If we consider the economy of shapes related to Euclid's geometry as a shape vocabulary, we can define shape algebras through geometrical transformation, traditionally these transformations are translation, rotation, reflection and scaling. The shape vocabulary of this nature is found in Computer Aided Design as well, the vocabulary is considerably simple so in order to create more complex forms, operations are available to combine different shapes and different transformations. As a result, two-dimensional C.A.D systems of drawing facilitate the creation of straight lines circles and arcs for example. This use of the computer doesn't influence the economy of shapes. It is the same design approach of the traditional hand driven linear design but with another media. The fact that linear design that used to be by drawn by hand is now created with a computer doesn't have a great architectural impact. It is replacing a two dimensional representation of an architectural building with another one. The second interpretation of the computer is related to the application of some sort of computer coding. Then, the computer is used creatively. The traditional software limitations are no longer a creative restriction when architects code.

Each new Information technology influences how we archive and communicate information the same applies in architecture. To illustrate, by the end of the Renaissance the use of orthographic drawings and perspective changed the way the information of the building is communicated for the purpose of its construction. This communication changes again with the use of computers in design and construction. For buildings to become material entities it is crucial to communicate the information required for its construction. The traditional two-

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[55] ?

dimensional drawing as section, plan and elevation is adequate for buildings with linear forms consisting of shapes from the Euclidean vocabulary of shapes. When the shapes and forms become more complex such as a double curved surface, volumes with inherent properties of topological or parametric design for example, then the reading of these shapes through two-dimensional representation is inadequate. Thus, if it is difficult to read the architectural document and imagine the form, then it is even more difficult to translate it into physical forms, in other words to construct it. For example, the fold for Eisenman, is a way to avoid the Cartesian grid and manifests a " a challenge - if not a catastrophe - for architecture's planometric means of representation, which simply cannot cope with the spatial complexities characteristics of the fold." Since the economy of shapes is changing from Euclidean based to non euclidean geometrical relations, intuitively we understand that it becomes more complex. A virtual three-dimensional model is a digital tool that facilitates the reading of complex forms.

COMPUTER OPERATED TOOLS & 3D MODELING

EARLY C.A.D SOFTWARES

The implementation of computers in architectural offices started sparsely in the 1980's. Jon Pittman recalls from his job experience at HOK in the 1980s that there was an employee whose responsibility entailed the scheduling of the use of the computer. This person negotiated the time each project manager was allowed to use the computer for. In 1985 the personal computer was commercialized and the problem of time scheduling was solved. As the price of the computer slowly cheapened, its use in architectural offices increased. From the the 1990's until today the use of computers in architectural design has grown exponentially. As a short historical overview, Eisenman's and Gehry's first use of computational software for architectural design are presented. The software Form*Z for Eisenman and Gehry's first use of C.A.T.I.A .

EISENMAN & YESSIOS

The digitalization of design tools in Eisenman's case started in 1989 when his office started using the predecessor of three dimensional model software Form*Z. In 1973, Christos Yessios, a professor of architecture and the software developer of Form*Z, wrote his Ph.D. thesis in Computer Aided Design thesis "Syntactic Structures and Procedures for Computable Site Planning". He described a language and grammar of shapes inspired by Noam Chomsky's generative grammars. Based on the linguistic method, the software could conclude the most advantageous spatial composition within a preset of design parameters. Form*Z originally began based on the collaboration of the logic structure of language with images ; it then evolved to establish a cognitive framework. “Following the canonical paradigm of form making, an array of predefined platonic shapes provides designers with the starting point for a series of controlled transformation to generate geometries whose limits are set by the individual *imagination.”*[56] Some aspects of the design could be coded and programmed, some others couldn't, some processes were limited by the computer while others were offering novelty. The design process had to adapt to the limitations of the computer but it offered at the same time the possibility of unpredictability in design, these facts started the predisposition of the architects as the author of a multiplicity of shapes rather than a singular determinate design. Yessos commenting on the use of computer aided design in a class with Eisenman declared

> *“At this time, we do not fully understand where it might lead us. We do not even fully understand the potential of what is already in place. Actually the potential appears to be virtually infinite. It is leading us to compositional schemes, which we could never have conceived on our own, but the computer is able to unfold for us. And yet, we programmed the computer; we told it what to do. This is not as paradoxical as it may sound. It certainly underlines the potential of the machine as a ‘reinforcer’ of our creative processes.”*[57]

The first time Form*Z was used by Eiseman was for the design of the Emory University Center for the Arts situated in Atlanta, Georgia; it was constructed between 1991 and 1993. The software made new operations available such as Boolean operations for example, volumes are combined after being transformed in some manner , surfaces are being folded and triangulated so planarity is controlled. Operating with a frame model was a different way of working, the design originating from a set of information allowed the extraction of drawings.

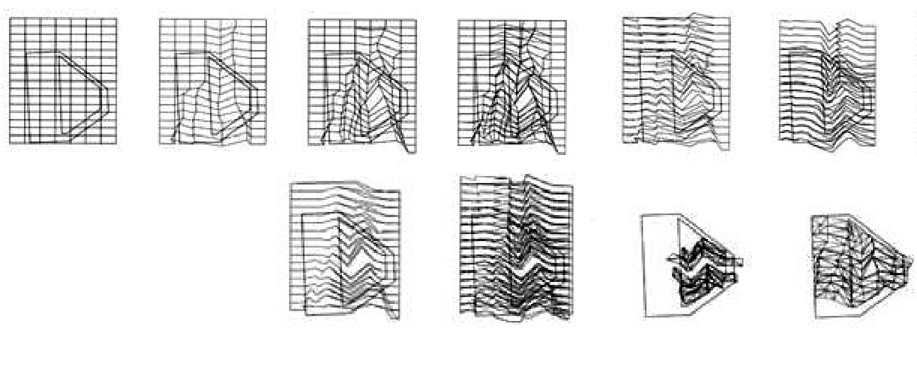

Figure 12. Peter Eisenman: Church 2000, Rome, 1996–1997.

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[56] Pierluigi Serraino, *“Form*Z: Its History and Impact on Design Practice”, in: “History of Form*Z”,* Pierluigi Serraino, Basel, Boston, Berlin: Birkhäuser, 2002, p.6

[57] Chris I. Yessios, *“A Fractal Studio”*, in: acadia 87, Proceedings of the Annual Conference of the Association for Computer Aided Design in Architecture, University of North Carolina, Nov. 1987, p. 1

FRANK GEHRY & JIM GLYMPH

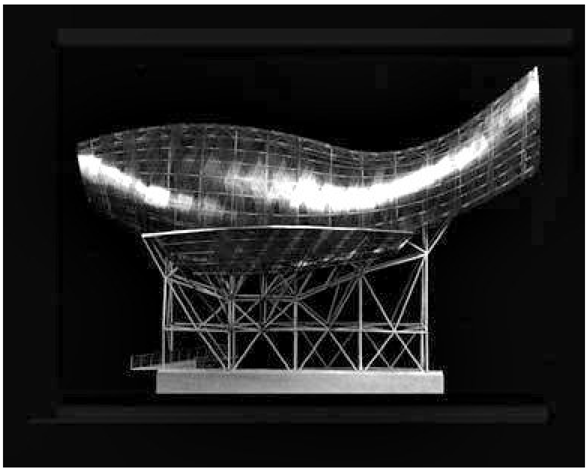

Figure 13 Gehry's Fish Sculpture (1992) Barcelona

Compared to other industries, architecture is quite late in using three dimensional digital modeling software and new technology in general. C.A.T.I.A. was already in use for twenty years in aircraft before it was used by Gehry's office. The modeling and manufacturing software was developed originally for the French aerospace industry (Dassault Systems). So a software originally created to design airplanes was used to design Gehry's Fish Sculpture (1992) a pavilion in Barcelona. Because of budget and time constraints, Jim Glymph, Gehry's partner opted for digital design to ensure that the complicated geometry could be described and constructed. The design of the pavilion started in the late 1980's. As is usual with Gehry's method, a physical model was created first then it is translated in a digital model. This digitalized version of the physical model offering a wire-frame model enables the structural engineers to analyze the structure. A physical model is them created with manual machines or computer operated machines to compare with the first physical model that was used during the conceptualization. Then, the digital model communicates the information for the construction and the assembly of the various components of the artifact. This process innovates a design process that doesn't involve paper. Architectural drawings are not needed for the first time. The information regarding the construction is united in a single model that the various parties involved in the process of the building have access to, the architect coordinates this information. In this continuous process of production, the digital information from the model is able to be used in various ways by various people who possibly will operate at different times in different places and even maybe in different time zones. The three-dimensional digital model is a very important part of the contract documents, all dimensions relative to the construction are derived from the digital file. Remarkably the digital model is a construction document used for legal issues and the construction process. Gehry and his office continued with this line of operations on numerous occasions amongst others the Experience Music Project in Seattle, and the Walt Disney Concert Hal 2003 in Los Angeles .

Gehry extracts digital data from a physical model whereas Eisenman uses the computer to design a generative process. In both cases though the possibility to generate and communicate construction information directly from the digital design information is a great novelty.

Figure 14 Gehry illustarted in an episode of the Simpsons

ALGORITHMIC DESIGN

As Mitchell states a designer who wants to expand his geometric freedom needs to control an additional amount of parameters in order to create innovative ideas.[58] Kostas Terzidis articulates the two interpretations of the use of the computer, a representational or creative tool, as follows :

> *"There is a fundamental difference between algorithmic and CAD related (or inspired) design. The difference is not only technical, representational, or graphical but also scientific, rational, methodological, and as such, intellectual. Algorithmic design employs an abstract symbolic language for representing ideas, concepts, and processes to be manipulated by a computer. It is a way of thinking, whose power is derived not only by the articulation of thoughts within the human mind but also, most importantly, by the extension of those thoughts using computational devices. In contrast, CAD related design is a graphical manipulation of predetermined elements or processes given to the designer as tools but whose potential capabilities have already been set in advanced."*[59]

[58] Mitchell William, *"Design Worlds and Fabrication machines"in"* Architecture *in the digital age design and manufacturing"Kolarevic Branko (ed),* Spon Press,New York 2003 p. 109

[59] Terzidis, Kostas. "Tool-Makers vs. Tool-Users (or both)?". Form Z | Joint Study Report. Cambridge, MA. 77-79. 2005-2006. P. 77

The computer when used with some sort of algorithmic design enables the designer to create shapes and tools and not restrict himself to the preset geometric choices of a C.A.D interface, simply put in the title of the article from which originates the above quote : *"Tool-Makers vs. Tool-Users (or both)?"*. Designers using the new media had the opportunity to create digitally generated forms. Architectural design is in its essence concerned with programming so most architects think in terms of programming, be that as it may, some are inclined to invest time into computational coding skills and possibly explore new concepts of space. Some programs offer an in-between solution, relations are still defined with the use of an interface, not a strict programming language but the software translates the dynamic definitions in an algorithm[60]. Both types of algorithmic design offer parameters that alter the design often unpredictably.

The introduction of computer aided design in architecture had a great impact since the computational facilities are starting to transform the hegemonic economy of shapes by changing our thought process and the architectural forms resulting from them. How do our tools influence our thoughts? Nietzsche stated that writing with a new tool, his typewriter "worked" on his thoughts[61]. Architecture is influenced predominantly by the thoughts, the intellectual equations of the architect, presumably these thoughts can be influenced by the use of the computer the same way Nietzsche's typewriter did.

New means of architectural representation offer the possibility of new architectural thought and production is freed from the restrictions of two-dimensional representation. Architects affected by the writings of Leibniz, Einstein or Deleuze might use non Euclidean geometry to explore new shapes. The economy of shapes changes with new digital processes of conception, for instance the use of topology in architectural design or parametric design. Topology can be a way to investigate new shapes, as it is "a branch of mathematics that studies the properties of objects that are preserved through deformation"[62]. Topological geometries are about spatial relations; it translates in architectural design in research of form rather than the making of form. As Kolarevic describes: "According to its mathematical definition, topology is a study of intrinsic, qualitative properties of geometric forms that are not normally affected by changes in sizes and shape, i.e. which remain invariant through continuous one-to-one transformations or elastic transformations, such as stretching or twisting."[63]

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60 For example the plug-in Grasshopper to the software Rhinoceros.

61 Friedrich Kittler, *"Grammophone, Film, Typewriter"*, translated by Geoffrey Winthrop-Young and Michael Wutz, Stanford: Stanford University Press, 1999.

62 Kolarevic Branko (ed) *"Introduction"in"* Achitecture *in the digital age design and manufacturing",* Spon Press,New York 2003. p.7

63 Kolarevic Branko (ed) *"Digital Morphogenesis "in"* Achitecture *in the digital age design and manufacturing",* Spon Press,New York 2003. p.18

Figure 15   topologically equivalent shapes

In Riemann's concept of space, an orthogonal rectangular box is the same as a curvy edged "blob", one object can evolve into another by changing the parameters of space within they each are defined, so objects are mapped to themselves and potentially to other objects. With topology is about relations and interconnections of shapes and not determinative processes of forms, consequently it involves less spatial distinctions and more spatial relations.

Parametric design as associative geometries, can provide for a powerful conception of architectural form by describing a range of possibilities, replacing in the process stable with variable, singularity with multiplicity. Using various parameters interconnected dynamically, designers could create an infinite number of similar objects, geometric manifestations of a previously articulated schema of variable dimensional, relational or operative dependencies. When those variables are assigned specific values, particular instances are created from a potentially infinite range of possibilities.

> *"Parametric approach to design, if consistently applied from its conceptual phase to its materialization, profoundly changes the entire nature and the established hierarchies of the building industry, as well as the role of the architect in the processes of building. For the first time in history, architects are designing not the specific shape of a building but a set of principles encoded as a sequence of parametric equations by which specific instances of the design can be generated and varied in time as needed. Parametric design calls for the rejection of fixed solutions and for an exploration of infinitely variable potentialities."*[64]

In parametric design, it is the geometric parameters of a particular design that are defined, not the shape. By defining and reconfiguring geometrical relationships, architects are inclined to explore various shapes in an nondeterministic way as opposed to describing a predefined shape. This has a great repercussion on the above mentioned economy of shapes.

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[64] Kolarevic Branko (ed)*"Digital Morphogenesis "in"* Achitecture *in the digital age design and manufacturing",* Spon Press,New York 2003. p.27

By changing the geometry architects code space with, from Euclidean to non-Euclidean innovations in architectural shapes and forms are taking place. These shapes have the tendency to increase with complexity compared to the previous vocabulary of shapes. This complexity is ill fitted in a two-dimensional representation even with the use of perspective, then again three-dimensional visualization encompasses the complexities of the architectural object with more ease since it enables a perspective view instantly from a sequence of many point's of view. Digital three-dimensional modeling offers a solution to the visualization of complex shapes emerging from the economy of shapes which in the process it transforms.

Figure 16. Kunsthaus (2003), Graz, Austria, Peter Cook and Colin Fournier.

Figure 17. Chesa Futura St. Moritz 2000-2004 Foster and Partners

Figure 18 Restaurant Georges (2000), Centre Pompidou, Paris, France, architects Jakob + Mac-Farlane.

Figure 19. Nationale-Nederlanden Building (1996), Prague, Czech Republic,Frank Gehry

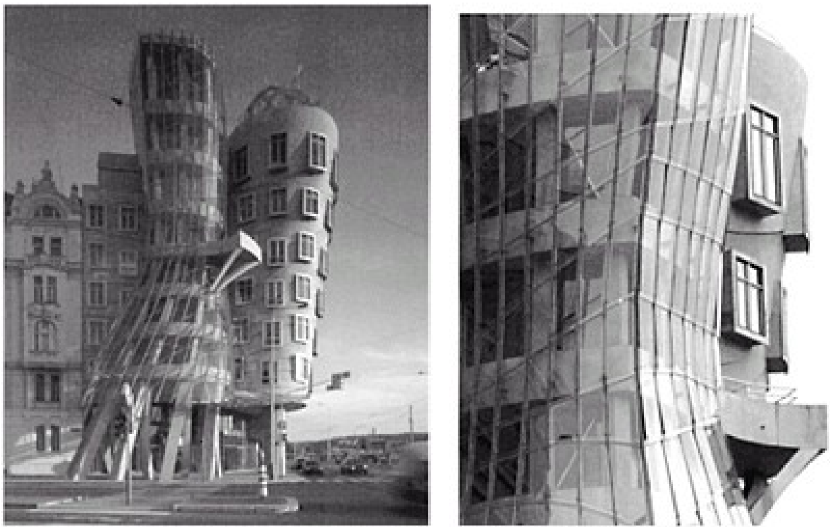

Figure 20. Guggenheim Museum (1997), Bilbao, Spain, Frank Gehry.

4D ANIMATION MODELING

Many architects have conceptually outgrown a classic CAD software, which in order to be dynamic and not deterministic should incorporate for example systems to describe relationships in the structure and physical phenomena's as the effects of time. Animation softwares contributed to architecture by including the notion of time into the design process. By exploring the design process through animation the designer investigates the dynamic plasticity of shapes. Animation techniques have the potential to simulate virtually the creation of new architectural objects.

Animation processes are used by experimental architects to unfold shapes through time, constructing components that continually change and interact with each other. There are many animation techniques, by adding the dimension of time to a process of formation or deformation, animation softwares offer the possibility of visualizing, observing and analyzing the metamorphosis of shapes. Temporal modeling technique are morphing for example, in which different shapes or volumes are blended to produce a hybrid range of designs that combine geometrically the two different shapes. Another animation technique as Kolarevic observes is

> *"keyshape (keyframe) animation, different states of an object (i.e. keyshapes or keyframes) are located at discrete points in time, and the software then computes through interpolation a smooth, animated, time-encoded transition between them. A designer could choose one of the interpolated states for further development, or could use the interpolation as an iterative modeling technique to produce instances of the object as it transitions, i.e. morphs from one state to another ."*[65]

Greg Lynn was one of the first architects to use animation software a form searching method and not only as representation. Besides being a tool for the architectural research of shapes, the notion of time is important in the architectural model in relation to assembling and sequencing structural components. Eventually the model can be fourth-dimensional, including all the information for the design, analysis and construction of the building but it can also integrate time-based information. Some computational design tools have the notion of time integrated in their process, thus offering a different approach to design. Through the metamorphosis of shapes and the possibility of chronological organization of the assembling in serial order of construction elements, the notion of time in computational design softwares offers

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[65] Kolarevic Branko (ed) "*Digital Morphogenesis*" in "*Architecture in the digital age design and manufacturing*" , Spon Press,New York 2003. p.34

a plethora of solutions from which emerges a final shape and the order in which to built it. Two dimensional drawings represent and communicate construction information but in the case of digital technologies as Kolarevic remarks, the design information *is* the construction information.[66] He also points out that digital technologies offer the possibility of a digital continuum from design to production. Design, analysis, representation, manufacturing and assembling of a building are possible from a digital file because the information is easily communicated and exchanged. Additionally, the geometrical information from the design can be communicated to a computer numerically controlled machine. Three-dimensional digital modeling conjointly with digital fabrication had a great impact on architecture notably by allowing novelties in the department of construction.

CONSTRUCTION TECHNOLOGY

The construction industry is changing with the introduction of machines controlled by computers to fabricate partly or totally components the of a building. The information age, offers novelties regarding the construction technology for example mass customization as opposed to mass production related to the industrial age. The development of modern architecture and beginning of the digital architecture relied both on new ideologies and aesthetic principles as well as innovations in the domain of technology.

INDUSTRIAL AGE AND TECHNOLOGICAL NOVELTIES

Some characteristics amongst others of modern architecture are simplicity, exposed structural elements, no unnecessary design detail and the Cartesian grid. Louis Sullivan (1856-1924) expressed his famous quote “Form follows function” quite representative of the ideology of the modern movement associated with the idea that a building makes its own statement through their structure and functionality. Clean lines, minimalist interiors, post and beam structures and the window as design are parameters often related to modern architecture. Mies van der Rohe stamps the modernist movement with the phrase “Less is More” expressing under one statement the aesthetic ideology of the modern movement. Mass production is highly linked with the modern movement through the new use of machine-made materials such as mass produced steel tubings.

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[66] Kolarevic Branko (ed) *Architecture in the digital age design and manufacturing* , Spon Press,New York 2003. p.10

The development of modern architecture relied both on new aesthetics principles and innovations in the domain of technology. The new use of materials such as concrete, iron, steel and glass gave new opportunities to an architecture partially restricted until then due to the properties of stone and wood. In the 20th century, space seems to acquire a new sense aiming to fulfill the new needs of living in the following of the industrial revolution.

The geometries of the twentieth century Modernism were, mainly driven by Fordian paradigms of industrial manufacturing, introducing to the building a production with the logics of standardization, prefabrication and on-site installation. Geometric simplicity is chosen over complexity and the repetitive use of low-cost mass-produced components.

The incorporation of movement into a static space was one of the ideals of modern architecture. However, the architecture that was described by modernists promoted movement in a dialogue of the interior and the exterior. The Industrial age challenged how architects design buildings but also how they construct them, the same occurs in the case of the information age. C.N.C machinery can fabricate unique, complex shaped components at a cost that is sometimes competitive. Difference and variety are not obligatory restrictions in this economy of production.

INFORMATION AGE AND TECHNOLOGICAL NOVELTIES

Digital fabrication in combination with dynamic design computational process offer architectural novelties on many levels. The complex shapes resulting from geometrical relations, of topological or associative nature for example , how are they transformed in physical architectural objects ? How are these often complicated shapes become forms with tangible dimensions ? It seems that architects who couple dynamic digital means of design along with digital means of fabrication are able to escape from the Cartesian economy of shapes.

It is only at the end of the 20th century that the design of architectural objects and their construction were affected by Computer Aided Modeling and Computer Aided Design. The difference between a machine controlled manually and a Computer Numerically Controlled machine is that a C.N.C machine moves along directions given by a programming language. By connecting the computer, the machine and the information of the topological digital model, we can fabricate architectural parts or a scaled prototype with C.N.C machines.

The architectural shapes and surfaces created digitally are mathematically described by Non Uniform Rational B-Splines. N.U.R.B.S are a computational method that allows describing complex surfaces. By interacting with control points, weights and knots curves or surfaces described by N.U.R.B.S can easily be altered. A parametric approach of design offers a plethora of possibilities and multiplicity principally by including variables.

> *"Another property of NURBS objects, which is of particular importance from a conceptual point of view, is that they are defined within a "local" parametric space, situated in the three-dimensional Cartesian geometric space within which the objects are represented. That parametric space is one-dimensional for NURBS curves, even though the curves exist in a three-dimensional geometric space. That one-dimensionality of curves is defined at a topological level by a single parameter commonly referred to as "U." Surfaces have two dimensions in the parametric space, often referred to as "U" and "V" in order to distinguish them from X, Y and Z of the Cartesian three-dimensional geometric realm. Isoparametric curves ("isoparms") are used to aid in the visualizing of NURBS surfaces through contouring in the "U" and "V" direction. These curves have a constant U or V parameter in the parametric NURBS math, and are similar to topographic contour lines that are used to represent constant elevations in landscape."p24*

C.N.C machines are divided in some categories in relation to the material process, including a subtractive, a two dimensional and an additive production process in addition to others . Laser-cutters, digital rooters with 3, 4 or 5 axes, 3D scanners , 3D and 4D printing machines to name just a few examples. C.N.C machines can also accurately alter a shape or position components with great accuracy like the robotic placement of architectural parts.

Two dimensional cutting of shapes in materials is a very popular process. Light in the case of the laser, a very sharp knife or water with a very high compression level are all methods to cut sheets of material. The motorized cutting device moves along 2 axes or it can be that the cutting bed that moves and the cutting device remains stable, or sometimes both can even move simultaneously. When the procedure involves the subtraction of material from another volume of material it is often done with more than two dimensions. Then again the drilling bit for example when carving a piece of wood can be moving or the surface upon which lies the wood can be moving but in contrast with two-dimensional cutting C.N.C machines it has a third dimension, depth . A machine that subtracts matter can work with 4 or 5 dimensions which means that the drilling bit is able to rotate in one or two directions. Process of additive materials also known as 3D printers, emerged in 1984 since its invention by Charles Hull, inventor of stereolithography and founder of 3D systems. [67] Today there are many ways of 3D printing. The digital model is organized two-dimensionally in thin layers of the same thickness which determine the definition of the final result; the coordinates of the layers is then communicated to the machine. 4D Printing is when the 3D printed object is capable of self organizing itself into a stable structure.

4D PRINTING

Skylar Tibbits, director of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT), with his team explores the development of self-assembly programmable materials and adaptive technologies for industrial application in building design and construction. The group studies programmable materials, self assembly, self-organization in a dynamic process they call 4D printing. 4D printing is like 3-D printing but with the added dimension of time, where the material is programed to change geometry under certain circumstances.

Digital design and digital means of fabrication offer the possibility of designing complex geometry and fabricate the components. Given this increase in complexity of the physical structures of buildings the processes of assembling these complex structures are often complicated. Assembly problems are for example, error propagation and difficult construction sequences that result from the increasing complexity of the information required to build complicated structures. Tibbits proposes to embed a programmed automation within the material elements in order to simplify the construction process. In his thesis he studied digital logic modules for self-guided-assembly of large-scale structures and argued that “if we want to build more complex structures than humanly possible today, then we need to embed discrete assembly information directly into our materials to self-guide the successful assembly of complex structures.”[68] In this case, 3D printing is used to create self-transforming objects with complex geometry. Tibbits and his colleagues address the difficulties presented with self-evolving complex structures. Printed structures that evolve through time are able to stretch, fold and bend showing that an object can be programmed to sense the environment and actively self-deform creating multi-purpose structures that can transform dynamically their geometry.

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[67] Hull, C. W. inventor; Apparatus for production of three-dimensional objects by stereolithography. *United States patent US 4,575,330. 1984.*

[68] Tibbits, S, *“Logic Matter: digital logic as heuristics for physical self-guided assembly,”* MIT, Department of Architecture & Department of Electrical Engineering and Computer Science, Masters Thesis, 2010. p.7

INTERACTIVE ARCHITECTURE

The unified concept of space and time of the fourth-dimensional continuum is partially illustrated in architecture by the notion of interactivity in design, materials and structure.

> *"As architectural conceptions of space move from the three dimensions of the Cartesian space to fourth-dimensional continuum of interactions between space and time, [...]. An architecture of warped multidimensional space would move beyond the mere manipulation of shapes and forms into the realm of events, influences and relationships of multiple dimensions."*[69]

The information society is replacing the industrial society, this fact in combination with the new notion of time offers the possibility of many changes in architecture. Information technology is not only about the contents of bits of information it is also about the way these bits are interconnected. This interconnection enables the reorganization of these bits in various ways. Interactivity is a key concept in restructuring the connections of bits of information. Interactivity in architecture captures the very complicated technical, scientific and aesthetic situation of the information society.

Concerning architectural design, dynamic systems of computation offer the possibility to develop and generate forms interactively through a sequence of parameter changes. Geometrical objects interact with each other, they connect opening up the possibility of many variations. Elements constantly evolve and change through time if mutual interactions exist between each parts. As Lynn describes, in place of a neutral abstract space, "the context of design becomes an active abstract space that directs from within a current of forces that can be stored as information in the shape of the form."[70] It is the interaction of information between the architect and the computer that allows the information to become eventually a form.

Interactive materials change their properties dynamically and are physically transformed in direct response to the external environment and/or its internal structure; they are composite materials that have their own sensors, actuators, and possess adaptive capabilities. An adaptive material can change its properties, its volume, opacity or color for example to readjust in accordance to some stimuli, internal or external. An active material is not only able to sense a

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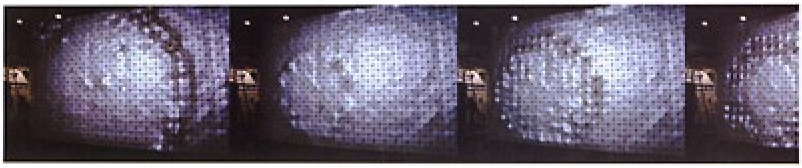
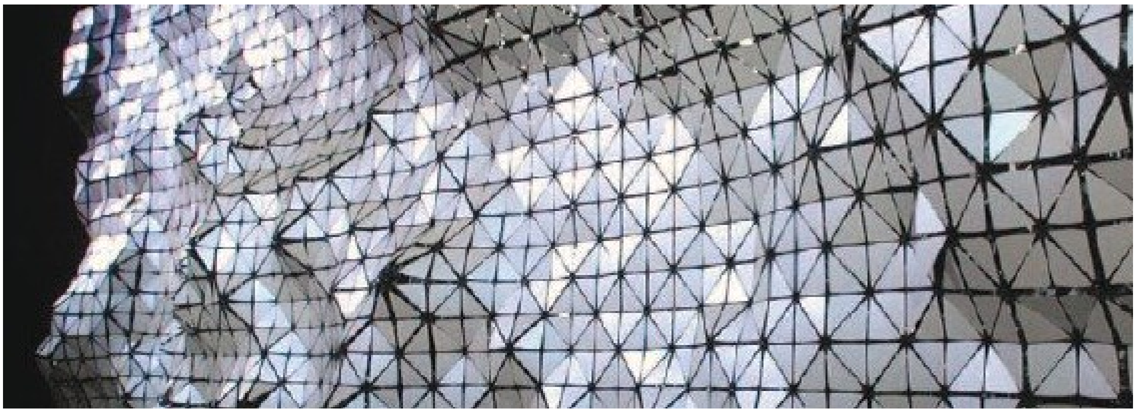
[69] Kolarevic Branko (ed) "*Digital Morphogenesis*" in "*Architecture in the digital age design and manufacturing*" , Spon Press,New York 2003. p.21
[70] Greg Lynn. Animate Form. Princeton: Princeton Architectural Press, 1998

new situation, but is also capable of performing a response. Interactive architecture is able to transform through its materiality as in the color or degree of opacity but is also able to change its shape and form as the Aegis Hyposurface project by Mark Goulthorpe demonstrates .

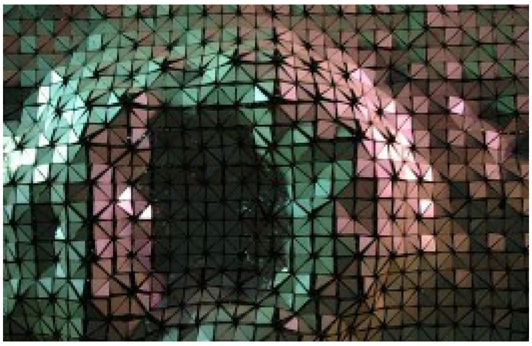




Physical interactivity in architecture is quite complex as it entails the transformation of space. In 1999, the interactive structure “Aegis Hyposurface” by dECOi Architects, won the first prize for the Birmingham hippodrome foyer art-work competition. It is a surface capable of dynamically reconfigure itself responding in real-time to various environmental changes. The surface is composed of many metallic surface, a flexible rubber membrane covered with many triangular metal surfaces. When the environment changes the surface transforms geometrically. Several thousand of pistons controlled digitally providing a real-time response enable the interaction. Goulthorpe explains that :

> *“ Effectively, Aegis is a dynamically reconfigurable screen where the calculating speed of the computer is deployed to a matrix of actuators which drive a “deep” elastic surface. The implicit suggestion is one of a physically-responsive architecture where the building develops an electronic central nervous system, the surfaces responding instinctively to any digital input (sound, movement, Internet,etc.)”*[71]

[71] Goulthorpe Mark “Scott points: Exploring principles of digital creativity

This project announces the feasibility of interactive, indeterminate dynamic forms. Forms that change through time and adapt to changes in the environment. The capacity of discovering forms by means of animated, dynamic, non-deterministic and non-linear systems of coordination allows digital design to generate unexpected outcomes. The behavior over time of non-linear systems cannot be easily understood because the elements that constitutes them are in a complicated web of interrelations and synergy . Composing a space of the information age, architecture could embody the concepts of multiplicity and simultaneity of the new concept of space-time as an ongoing exchange of information between its user and the environment.

SEMIOTICS OF DYNAMIC ARCHITECTURE.

Architecture is a particular challenge to semiotics because most of architectural objects are not designed to communicate but to function. However, our phenomenological experience of architecture intuitively tells us that that we do experience architecture as communication at the same time that we use its functionality. In the Digital Age, architecture using the language of information can highly augment the communicative efficency of architectural objects. As Umberto Eco explains in “Function and sign:the semiotics of architecture”, architectural objects as significative forms (codes that are based on the coherence from usage) is interpretable in terms of communication. The ability of architecture to communicate its functions is based on codes. Architectural codes, technical, syntactic or semantic are quite restrictive, they offer limited possibilities of operations as they don't rely on the model of a language but a system of rhetorical formulas. By using exclusively these codes with preset solutions architecture is very l imitated in terms of novelty. The possibility of innovation is possible when architecture goes

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” in “*Architecture in the digital age design and manufacturing*” , Spon Press,New York 2003. p.21

against rhetorical predicaments as the message architecture conveys is able of higher information content. This does not mean that architecture moves away entirely from its own codes but that it includes external codes in order to be able to achieve novelty. With the external code of programming added to the internal architectural significative codes architectural communicative novelties are possible. With kinetic and interactive architecture, the architectural object through operation of its system of stimulative sign-vehicles is able to be designed for variables primary functions and open secondary functions, open in the sense that they might be redetermined by future codes. An architectural dynamic object is able to use a multiplicity of functions in a possible continuous reinterpretation of the reading of these functions.

CONCLUSION

Four-dimensional architectural concepts of space are partially represented by interactions of space and time in interactive architecture.

The emergence of the notion of space-time in the beginning of the 20th-century in various cultural branches combined with the emergence of the information age influenced thoroughly architecture. The new notion of time changed how we conceptualize space because we code this space with non-Euclidean geometry and the computer as a new media transformed how we represent this space and supposedly how we think about this concept of space. The conception and design of space are affected and so is the construction of architectural objects . It is argued in this paper that the paradigm shift of the notion of time involved a new notion of space in architecture related to space-time which is expressed with new dynamic relations of spatiality as a result. The notion of time and space changed in physics; they also changed in philosophy as the metaphysics of relative physics posed new questions and new discussions.

Additionally the information Age and the computer as a new media transformed how we represent this space and supposedly how we think about this new concept of space. Architectural representation has greatly been impacted by digital tools of architectural design, passing from two-dimensional drawings to three-dimensional virtual models and sometimes four-dimensional models that include temporal information. The virtual model is able to communicate information on many levels, including data destined for C.N.C machinery. The notion of space-time and movement is accounted for architecture in many ways; in digital design with animation, in digital fabrication with 4D printing and in the architectural object in general with Kinetic architecture and interactive architecture. Interactivity in architecture connects the subject with the architectural object in a reciprocal manner. It seems that we are slowly moving out from the mechanical space of the Modernists and that we are starting to design the interrelated space of information with the new technology available to us.

The Cartesian economy of shapes changed because of the connection of the new notion of time and information technology. The Bergsonian meaning of duration by posing a topological geometric method in opposition to the Cartesian scientific method begins a change in perception. Bergson argues that the Cartesian method is confused about the structure of movement between the parts and the whole. The dynamism of a system is synergistic. Fuller explains that “Synergy means: behaviors of whole systems, and a minimum system would be two, behaviors of whole systems unpredicted by behavior of any of the parts of the system, when the parts are considered separately, one from the other.” Thus, the architectural Cartesian economy of shapes transforms into a architectural economy of dynamic shapes that supports the mobile condition of our time, possible with the digital infrastructure that the information age offers.

Contemporary cultures are heterogeneous and complex, the dualistic vision of the Cartesian method is a great intellectual tool but is not adequate for the new level of complexity. The concept of Multiplicity appears more suitable as it promotes internal dynamic relations. “Social development is inseparable from the changes in the technological infrastructure through which many of the activities are carried out.”[72] The correlation between social developments and design in the digital age is illustrated by our dynamic network society and architecture of kinetic and interactive nature. Technology as an active and transformative entity of cultural and architectural artifacts, offers relations based on interactions with cultural stimuli. The people constituting society in the digital age are like “the cells of an organism nodes in a richly interwoven communications network, transmitting and receiving, coding and decoding.”[73] Since our actions and movements are dynamic and unfold through time, we program dynamic comportments subsequently, space should be dynamic, performative and informative too. Multifunctionality and interactive activities of the information society define the needs of the information city.

With design aided by a software based on differential calculus for example, architectural forms changed “from fragmented polygonal rectilinearity towards smooth continuous splinal curve-linearity, [...] subverting both the modernist box and its deconstructionist remains.” The economy of shapes is generally more curved and has a new quality of fluidity and dynamic

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72 Castells M. *“The Rise of the Network Society, The Information Age: Economy, Society and Culture”,* Vol. I.. Cambridge, MA; Oxford, UK: Blackwell, 1996.

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related to itself illustrating formally a “digital expressionism”[74]. More deeply architecture by including the fourth dimension within its design and fabrication with the aid of digital tools is changing conceptually as well, beginning its transition from a static concept of space to a dynamic concept of space-time as a system of interactions.

How we perceive this new space and how architecture needs new semantics to explain its new informational capabilities seems to be worth further research. The relations of time, space, architecture and the invention of cinematography are linked, and the impact that the new visual media had on our perception in four-dimensions and how it influenced our cognitive framework could be studied. Perhaps our ability to edit time in memory the same way a “montage” in a film rearranges the rhythm of a movie influences our perception.

The research of the impact of the notion of time introduced by the theory of relativity in regards to architecture in the information age shows that we are in a transitional phase passing from the static Newtonian concept of space to the dynamic concept of space of Einstein. As Lynn described in *“Animate Form”* we are shifting “ from a passive space of static coordinates to an active space of interactions.”[75] If time is relative, so is space. The unified concept of space-time is architecturally represented with interactive design and interactive structures. The architectural four-dimensional space in the context of the digital technology is dynamic, interactive, multiple and continuous. Animation techniques combining dynamic softwares and the notion of time in design offer an interaction between the information and the designer that produce a multiplicity of dynamic shapes. Dynamic materials and forms that unfold through time represent architecture's formal representation of the new notion of time. Interactive architecture supported by a technology that allows real-time reciprocal response of the architectural object with the subject and/or the environment is emblematic. The simultaneity of information between the structure geometrical adaptive capabilities offer endless possibilities.

The Cartesian economy of space is slowly transformed into a non-metric economy of shapes of Riemaniann geometric nature. This is illustrated by the use of dynamic systems with the term dimension related to the manifold, the space of the manifold is then “the space of possible states”. By using local information such as the transformation of degrees in curvature instead of rigid lenghts shapes described with non metric systems, the economy of shapes is changing. In modern architecture The incorporation of movement into a static space was one of the ideals of modern architecture. However, the architecture that was described by modernists promoted

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75 courses.arch.ntua.gr/fsr/140262/animate_form.pdf

mainly movement in a dialogue of the interior and the exterior. As Kwinter mentions in “ The problematic of time entails a challenge to the primacy of the role of space, and the reintroduction of the classical problem of becoming in opposition to that of Being.” The new economy of shapes is always redefining itself because it is constituted of shapes that are not determined but dynamic as they potentially remodel themselves constantly.

In modernism the building is either understood as a sequence of static images that are connected by a moving plan, guided by circulation, by movement or the buildings' surfaces morphologically display motion for a static viewer. Either we move and connect between still images of the building or the building simulates movement. The condition of staticity in modern architecture is starting to be questioned and the notion of space and time are intermingled in the way a story board describes movement before filming the action. Story board is to modern architecture what film is to Digital Architecture. Cinema is very important in the 20th-century, it greatly influenced western societies and offers a dynamic and plastic use of time representative of how our memory works. In the Digital Age even when shapes and forms are not literally dynamic they still carry symbolically this property because of external semiotic codes it is not the same as the simulation of movement of the building, as the forms of the avant-guard architects of the new notion of time represent a frozen moment in time of a movement, like a still image of a film.

Technologically, modern architecture had a technology of mass production available whereas digital architecture has the possibility of mass- customization, meaning that besides the entity of the building being unique now so can be the parts constituting it. Aesthetically the simplicity and minimalism that characterizes many modernists buildings is replaced with complexity and multiplicity. Thus, the economy of shapes of the digital age is representing the continuous becoming of “the space of possible states”. Using Bauman's description of the translation of “solid modernity” to “liquid modernity” as a metaphor for digital architecture, then interactive architecture symbolizes the liquid crystallization of the spirit of our time able to have both solid and fluid properties. The digital age offers the technological infrastructure to support an architecture that aims to fulfill the needs of living in the 21st century while also celebrating the differences of heterogeneous space within their own unity. Architecture could become an allegory of the digital society where everyone is unique just like everybody else.

BIBLIOGRAPHY

1. Adams Tim, “***Diagrams of Interface, or, Deleuze and Gauttari’s Legacy to Architects”***, University of Western Australia: Deleuze Symposium, 1996. http://www.academia.edu/2010882/Diagrams_of_Interface_or_Deleuze_and_Gauttari_s_Legacy_to_Architects. Last accessed in February 2015

2. Basset Bruce, Edney Ralph , ***“Introducing relativity”***, Malta: Gutenberg Press, 2002.

3. Bergson Henri, ***“Matter and Memory”*** (1896),translated by Nancy Margaret Paul and W. Scott Palmer, New York: Zone Books, 1991.

4. Blundell Jones Peter , Eamonn Canniffe, ***“Modern Architecture Through Case Studies 1945 to 1990”***, U.S.A: Architectural press ,2007 .

5. Braidotti Rosi, Pisters Patricia (eds.), “***Revisiting normativity with Deleuze”*** , New York : Bloomsbury, 2012.

6. Breslin L, “***From the Savage to the Nomad: Critical Interventions in Contemporary Japanese Architecture”,***The New Japanese Architecture,ed. Botand Bognar. New York: Rizzoli, 1990.

7. Buckminster fuller Richard, “***Nine chains to the moon”*** Carbondale:Southern Illinois University Press, 1938.

8. Buckminster Fuller, “***What I Have Learned VIII, How Little I Know”***, The Saturday Review, pp. 29-31, November 12 1966. http://64.62.200.70/PERIODICAL/PDF/SaturdayRev-1966nov12/31-34/ Last accessed in February 2015

9. Castells M. ***“The Rise of the Network Society, The Information Age: Economy, Society and Culture”,*** Vol. I.. Cambridge, MA; Oxford, UK: Blackwell, 1996.

10. Chavel I. , ***“Riemannian geometry, a modern introduction”***, Cambridge: Cambridge University Press,1993.

11. Cohen, J ***“Le Corbusier’s Modulor and the Debate on Proportion in France”*** Architectural Histories, 2014. ,

http://dx.doi.org/10.5334/ah.by
Last accessed in February 2015

12. DeLanda Manuel, ***"Intensive Science & Virtual Philosophy"***, Bloomsbury Revelations, 2013
http://roundtable.kein.org/sites/newtable.kein.org/files/DeLandaintensive_science_and_virtual_1.pdf
Last accessed in February 2015

13. Deleuze Gilles, ***"Bergsonism"*** (1966), translated by Hugh Tomlinson and Barbara Habberjam, New York: Zone Books, 1991.

14. Deleuze Gilles, ***"Difference and Repetition"***, New York :Columbia University Press, 1994

15. Deleuze Gilles , ***"Le pli : Leibniz et le baroque"***, Paris: Minuit, 1988.

16. Deleuze Gilles, ***"The Fold – Leibniz and the Baroque: The Pleats of Matter"***, Architectural Design, Folding Architecture, 1993.

17. Duffy Simon B. (ed.), ***" Virtual Mathematics: the logic of difference"***, Manchester: Clinamen Press, 2006.

18. Einstein Albert, ***"Comment je vois le monde"***, translated by Maurice Solovine and Regis Hanrion, France : champs flammarion, 1979

19. Einstein Albert, ***"The meaning of relativity"***, Bristol: Science Paperback, 1980 [1922].

20. Einstein Albert, ***"Relativity, The Special and General Theory"***, New York: Pi Press, 2005 [1920]

21. Eisenman Peter, "***Architect-designed Birdhouses"***, A+U:275, August, 1993.

22. Eisenman Peter **, *"Folding in Time: the singularity of Rebstock",*** New York D: Columbia documents of architecture and theory, volume II, 1993.

23. Eisenman Peter "***Visions Unfolding: Architecture in the Age of Electronic Media"*** in ***"The Digital Turn in Architecture 1992-2010: AD Reader"*** ,Carpo Mario (ed.) AD September–October 1992.

24. Friedrich Kittler, ***"Grammophone, Film, Typewriter",*** translated by Geoffrey Winthrop-Young and Michael Wutz, Stanford: Stanford University Press, 1999, p. 200.

25. Giedion Sigfried, ***"Space, Time and Architecture -The Growth of A New Tradition"*** Cambridge: Harvard University Press, 1954 [1941].

26. Gleick James , ***"The Information: A History, a Theory, a Flood"***, U.K: Fourth Estate Paperback, 2012.

27. Guerlac Suzanne, ***"Thinking in Time, An Introduction to Henri Bergson"***, Ithaca United states:Cornell University Press, 2006.

28. Gül Kaçmaz Erk and Belkıs Uluoğlu ,***"Changing Paradigms in Space Theories :Recapturing 20th Century Architectural History"***, International Journal of Architectural Research

Archnet IJAR, Volume 7 - Issue 1 – March 2013 .

29. Gunter, P. A. Y. ***"Bergson and the Evolution of Physics",*** Knoxville, University of Tennessee Press,1969.

30. Henderson, Linda Dalrymple, ***"The Fourth Dimension and Non-Euclidean Geometry in Modern Art."*** Princeton, NJ: Princeton University Press, 1983.

31. Howard Don A.***, "Einstein's Philosophy of Science"***, *The Stanford Encyclopedia of Philosophy* (Summer 2010 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/sum2010/entries/einstein-philscience/>.

Last accessed in February 2015

32. Iwamoto Lisa , ***"Digital Fabrications, Architectural and Material Techniques"*** .

33. Klein Martin J. , *Paul Ehrenfest: The Making of a Theoretical Physicist* (1970), Vol. 1, 315

34. Kline Morris, ***"Mathematical Thought from Ancient to Modern Times"***, Vol. 3,New York: Oxford University Press, 1972.
35.
36. Kolarevic Branko (edited by) ***"Architecture in the digital age design and manufacturing"*** , New York: Spon Press,2003.

37. Kwinter Sanford ***, "Architectures of Time: Toward a Theory of the Event in Modernist Culture"*** MIT Press, 2001.

38. Lawlor, Leonard and Moulard Leonard, Valentine, ***"Henri Bergson"***, *The Stanford Encyclopedia of Philosophy* (Winter 2013 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/win2013/entries/bergson/>.

Last accessed in February 2015

39. Le Corbusier***, "Le Modulor: Essai sur une mesure harmonique à l'échelle humaine, applicable universellement à l'architecture et à la mécanique"***. Boulogne: Éditions de l'Architecture d'aujourd'hui,1950.

40. Le Corbusier, ***"Modulor 2: La parole est aux usagers"***. Boulogne-Billancourt: Éditions de l'Architecture daujourd'hui, 1955.

41. Le Corbusier, ***"The Modulor: A Harmonious Measure to the Human Scale Universally Applicable to Architecture and Mechanics"***. London: Faber & Faber. 1956.

42. Lynn Greg, "***Folding"*** , Folding in Architecture: guest edited by Greg Lynn, Architectural design, vol 63, 1993.

43. Maurin Krzysztof, ***"The Riemann Legacy Riemannian Ideas"*** in Mathematics and Physics, Mathematics and Its Applications, Vol. 417, Springer 1997.

44. Milton Cameron, "*Albert Einstein, Frank Lloyd Wright, Le Corbusier, and the Future of the American City"*, Institute for advanced studies, Spring issue, 2014.
https://www.ias.edu/ias-letter/cameron-einstein
Last accessed in February 2015

45. Newton Isaac, ***"Scholium to the Definitions in Philosophiae Naturalis Principia Mathematica"***,pp. 6-12, Bk. 1 (1689); trans. Andrew Motte (1729), rev. Florian Cajori, Berkeley: University of California Press, 1934.

46. Padovan Richard, ***"Proportion: Science, Philosophy, Architecture"*** , London: Richard Taylor and Francis, 1999 p.35 320,25,316 ?

47. Rawes Peg, ***"Space,geometry and aesthetics,Through Kant and towards Deleuze"***, U.K: Palgrave Macmillan, 2008.

48. Robbins, S. E. ***"Special Relativity and Perception: The Singular Time of Psychology & Physics"***, in Journal of Consciousness Exploration & Research | Vol. 1 | Issue 5 | Pages 529-559 | July 2010

49. Rocker Ingeborg M. ***"Architectures of the Digital Realm: Experimentations by PeterEisenman | Frank O. Gehry."*** In J. Gleiter, N. Korrek, G. Zimmerman (Hg.), https://e-pub.uni-weimar.de/opus4/files/1332/rocker.pdf

50. Rynasiewicz, Robert, ***"Newton's Views on Space, Time, and Motion"***, The Stanford Encyclopedia of Philosophy , Edward N. Zalta (ed.), 2014. URL=<http://plato.stanford.edu/archives/sum2014/entries/newton-stm/>.
Last accessed in February 2015.

51. Shannon Claude E,***"AMathematical Theory of Communication"***,Bell System Technical Journal 1948.

52. Simon B. Duffy**, *"Deleuze and the History of Mathematics: In Defense of the "New"*,** Bloomsbury, 2013.

53. Smith Daniel and Protevi John, "***Gilles Deleuze"***, *The Stanford Encyclopedia of Philosophy* , Edward N. Zalta (ed.), 2013.
URL = <http://plato.stanford.edu/archives/spr2013/entries/deleuze/>.
Last accessed in February 2015

54. Snyder Robert, ***"Buckminster Fuller : scénario pour une autobiographie"*** ,translation Didier Semin,Paris: Images Modernes ,2004.

55. Stalder Felix, ***"The Network Paradigm: Social Formations in the Age of Information"***, Society and Culture, Vol. I.. Cambridge, MA; Oxford, UK: Blackwell, 1996.

56. Tampio Nicholas, ***"Multiplicity",*** Encyclopedia of Political Theory. 2010. SAGE Publications, 2010. <http://www.sageereference.com/politicaltheory/Article_n294.html>. Last accessed in February 2015

57. Terzidis Kostas , *"Expressive Form : A conceptual approach to computational design"*,, LONDON NEW YORK; Spon Press , 2003.

58. Terzidis, Kostas. ***"Tool-Makers vs. Tool-Users (or both)?"***. Cambridge:MA:77-79,Form Z, Joint Study Report, 2005-2006.

59. Tibbits, S, *"4D Printing: Multi-Material Shape Change"*, Archit Design, 84: 116–121, 2014

60. Tibbits Skylar & Dan Raviv, Wei Zhao, Carrie McKnelly, Athina Papadopoulou, Achuta Kadambi, Boxin Shi, Shai Hirsch, Daniel Dikovsky, Michael Zyracki, Carlos Olguin, Ramesh Raskar , *"Active Printed Materials for Complex Self-Evolving Deformations,"* Nature: Scientific Reports, 4, 7422 , 2014

61. Tibbits, S. *"From Digital Materials to Self-Assembly,"* Proceedings of the 100th Annual ACSA Conference, Boston, MA, 2012. https://blonsway.expressions.syr.edu/beyonddigital/files/2012/02/ACSA_ReSubmission_SJET_opt.pdf

62. Tibbits, S, *"Logic Matter: digital logic as heuristics for physical self-guided assembly,"* MIT, Department of Architecture & Department of Electrical Engineering and Computer Science, Masters Thesis, 2010. . http://hdl.handle.net/1721.1/64566

63. Tschumi Bernard, ***"The Architectural Paradox"*** in Theory Since 1968 ,Michael K. Hays ed. Architecture, Cambridge, Massachusetts; London, England: MIT Press, 2000 .

64. Villani, Arnaud. " *La guêpe et l'orchidée: Essai sur Gilles Deleuze"*. Paris: Éditions Belin.*1999*

65. Wiener Norbert,***"Cybernetics: Or Control and Communication in the Animal and the***

Machine".Paris,(Hermann&Cie)&Camb.Mass.(MITPress), 1948.

66. Williams James , "***Gilles Deleuze's Philosophy of Time: A Critical Introduction and Guide***, Edinburgh:University Press, 2011**.**

67. Wright Frank Lloyd***, "Modern Architecture*****:** ***Being the Kahn Lectures for 1930"***. Front Cover.. Southern Illinois: University Press, 1931.