Adriana Rossi

Department of Civil Engineering
Second University of Naples
Real casa dell'Annunziata
Via Roma, 29
81031 Aversa (Caserta) ITALY
adriana.rossi@unina2.it

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Research

From Drawing to Technical Drawing

Abstract. It is in the early Middle Ages that the demonstrative effectiveness of drawing begins to be correlated to mathematical description, thus laying the foundations for the geometrical conceptualization that technical drawing makes measurable. The biunivocal procedures that make it possible to transcribe three-dimensional shapes and to trace from these their exact collocation in space, their real size and their real shape, arose from the experience of specialized building site craftsmen and from the study of classical works. The new figure emerged that of the master mason who could draw and interpret designs. The need to show or to see what the end product would look like before it was actually built brought about the refinement of a drawing system from which the professional figure of the architect emerged.

It is in the early Middle Ages that the demonstrative effectiveness of drawing begins to be correlated to mathematical description, thus laying the foundations for the geometrical conceptualization that technical drawing makes measurable. The biunivocal procedures that make it possible to transcribe three-dimensional shapes and to trace from these their exact collocation in space, their real size and their real shape, arose from the experience of specialized building site craftsmen and from the study of classical works which were consulted more often than one would be inclined to think at the monastery libraries and the cultural centers that were beginning to flourish around the most enlightened courts in Europe [Le Goff 1981].

Eugène-Emmanuel Viollet-le-Duc (1814-1879) was the first to point out that mediaeval building site practice not only followed a set of rules to dimension spaces, but also a method according to which parts were ordered in succession. In complete disagreement with his contemporaries, who believed that Gothic art lacked symmetry,[1] the French scholar proved that Gothic cathedrals were not the result of an empirically improvised building practice, but were in fact remarkable buildings that were well proportioned in every part, if one knew how to look at them in the light of the fixed and constant rules of the renewed aesthetics [Antolini 1817]. These rules were based on the teachings of Thomas Aquinas (1225-1274), who suggested conformity of object to intellect a guideline towards the pursuit of *veritas* [Eco 1956,1959,1987,1970].[2] In the context of the mediaeval building site this approach meant that solutions were sought bearing in mind the nature of the landscape and place and the opportunities they offered: pre-existing elements were harmonized with vaults and arches, leftover material was re-used and the "areas" (*saltus*) in which the voids and the planes were to be distributed were built using "dividers" (*rigores*) [Lenza 2002]. Ratios and proportions were calculated substituting the fixed point identified by the reference pickets with numbers. The transcription criterion was derived from the teachings of Leonardo Pisano (1170-1240), the mathematician who introduced the Hindu-Arabic place-value decimal system and the use of Arabic numerals into Europe.[3] Fibonacci, as he was known, was the son of a wealthy merchant, Guglielmo Fibonacci. He used fractions (from the Latin *fractus*) to teach how to obtain measurements to those who, like his father, needed to measure things which were not only or always directly related to the length of the "cane," a sort of

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ruler graded according to the length of the palm, foot and arm of a person of average height. In a chapter of his 1202 *Liber Abaci* concerning the division of the cane, Leonardo Pisano introduces classes of equivalence relations capable of "breaking down" lengths and thus solving "practical geometry" problems on the building site. This system allowed for a re-interpretation of the mean proportional theory ascribed to Pythagoras and brought to a sophisticated level of abstraction by his friend Archytas of Tarentum (428-347 B.C.), a disciple of Philolaus.[4] In the *Timaeus*, widely known in the Middle Ages thanks to an abridged and commented translation by Calcidius,[5] Plato claimed that it was impossible to combine two things well without a third. A link was needed between them and there was no better link than the one that connects them to one another as a whole.

This, which according to the philosopher represented the nature of proportion [Wittkower 1962: 101ff], had been studied by Archytas, who analyzed consonant intervals and proposed a new division of the tetrachords (enharmonic, chromatic and diatonic) to which a new definition of three different types of relationships was linked. The algorithms needed to obtain, through a finite number of steps, the properties that link three quantities in succession (a, b, c) were transcribed by Porphyry of Tyre[6] (233-305 A.D.) and referred to by Eudemus of Rhodes (370-300 BC) in his Commentary on Aristotle's Physics:[7]

– *the arithmetical relationship* in which the difference between the terms is constant:

$$a - b = b - c$$

– *the geometrical relationships* obtained when the quotients are constant:

$$a : b = b : c$$

– *the harmonic relationships* obtained by the inverse in arithmetical proportion:

$$\frac{1}{a} - \frac{1}{b} = \frac{1}{b} - \frac{1}{c}$$

$$(b - a) : a = (c - b) : c$$

From the respective definitions the means are derived:

– *Arithmetical* (6: 9: 12), when the terms exceed each other so that the first exceeds the second as the second exceeds the third

$$b = (a + c)/2 \,;$$

– *Geometrical* (6: 12: 24), obtained when the terms are such that the first is to the second as the second is to the third. Here the interval of the greater terms is equal to the one of the lesser terms

$$b = \sqrt{ac} \,;$$

– *Harmonic* (6: 8: 12), also called *subcontrary* as they derive from the musical octave in which the second term exceeds the first as the as it exceeds the third

$$b = \frac{2ac}{(a + c)} \,.$$

How to determine mean proportionals with numbers or letters had become widespread knowledge, thanks also to a sort of manual by Johannes de Sacrobosco, entitled *Algorismus vulgaris* or *Algorismus de integris* (1250), which taught how to perform calculations using addition, subtraction, multiplication, division, square and cube roots, or the inverse elevation to a power. The groups of numbers, or as we would say today, the fields of algebraic existence, prompted the comparison of solutions which left the commensuration criteria unchanged if one substituted a concrete modulus with an abstract one represented by a number. The analytical procedure allowed for the quantification of the mean of Phidias, called Φ after the Greek sculptor of the Parthenon who is reputed to have used the diameter of the column to determine the rhythmic division of the temple according to the "right harmonic proportions". The use of measurements systems such as that of the "cane," which divided lengths so that the sum of the first two quantities remained constant, a procedure theoretically formalized by Fibonacci himself, paved the way for the computation of harmonic relationships. How to divide a segment in mean and extreme ratio was a problem which had been solved from a geometric point of view many centuries before: proposition XXX of Book IV of Euclid's *Elements* fixed a point on a segment "so that it was to the greater as the greater was to the lesser". A proportion between the parts could be now calculated by solving a second degree equation in x.

The total length of a, segment being known, the calculation:

$$a : x = x : (a - x)$$

leads to a standard formula:

$$x^2 + ax - a^2 = 0$$

The actual concrete problem allowed for one possible solution. For $a = 1$ the positive value of the root is a number whose characteristics cannot be transcribed as a rational fraction

$$x = \frac{\sqrt{5} - 1}{2} = 0.6180339\ldots$$

Assuming that there exists a positive real number such that:

$$\frac{1}{x} = 1 + x$$

We get the initial expression whereby its positive root x=0.6180339… defines the number Φ :

$$\frac{1}{0.6180339} = 1 + 0.6180339 = 1.6180339\ldots = \Phi .$$

This is believed by many to be a recurrent constant in the proportions of the temple dedicated to Athena Parthenos. It can be shown that this quantity can be obtained as an approximation of an arithmetic succession. By studying the problem of how many rabbits could be begotten in a year starting with one pair,[8] Fibonacci manages to prove that given the succession (sequence) of numbers:

(1), 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377...

The ratio between two consecutive terms approximates to the constant:

1/1; 2/1; 3/2; 5/3; 8/5; 13/8; 21/13; 34/21; 55/34, 89/55; 144/89; …

1 ; 2; 1.5; 1.666; 1.6; 1.625; 1.615; 1.619; 1.617; 1.6181; 1.6180; …

It is observed that

$$\Phi^2 = 1 + \Phi$$

$$\frac{1}{\Phi} = \frac{\sqrt{5}-1}{2} = 0.6180339\ldots$$

The first expression shows that Φ is a solution of the second degree equation

$$\Phi^2 - \Phi - 1 = 0\,,$$

so one returns to the original expression, considered capable of guaranteeing aesthetic and therefore functional and static reliability in that it was derived from the laws of organic differentiation. Quite familiar with the mathematical concepts that during the Middle Ages made Euclidean geometry computable, Viollet-le-Duc tried to empirically de-construct the surveyed buildings to seek in the configuration of the elevation and plans the necessary criteria to re-trace the design work. Substituting the building site tools with compass and ruler the scholar examined the drawing of the naves considering the rectangles and the squares subtending their spans as sums of right triangles, equilateral and isosceles triangles or, as Viollet would have called them, Egyptian triangles as they were believed to be derived from the properties of the monuments built in the Valley of Kings[9] (fig.1).

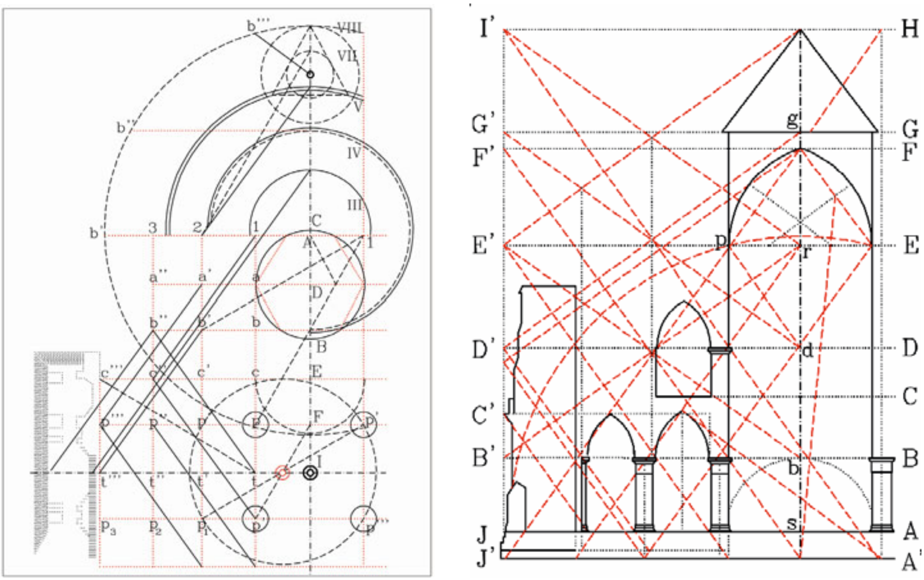

Fig. 1. Viollet–le-Duc. Plan and section of Notre Dame de Paris. Re-elaboration in CAD by F.S. Golia

According to Herodotus (*Histories* II, 124; 5) the matrix-section of the pyramid of Cheops is an isosceles triangle that can be divided by its height into two mirror-symmetric right angle triangles (fig.2) [Taylor 1859; Smyth 1978].

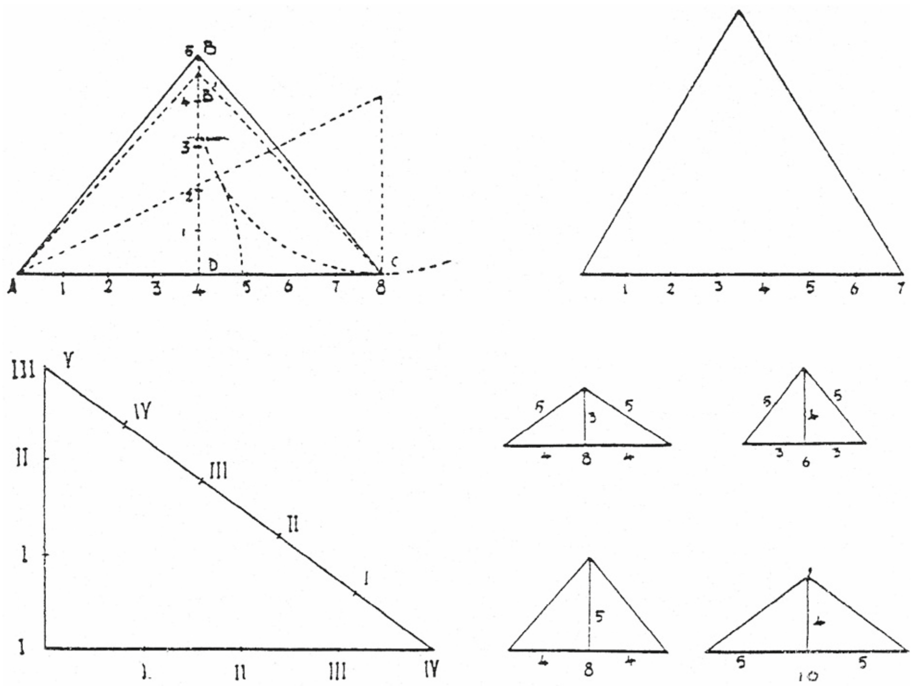

Fig. 2. Geometries widely used on medieval building sites derived from the model of the Pyramid of Cheops. Harmonic triangles: stable (base 8, height 5) and Egyptian (base 8, height 4.94432)

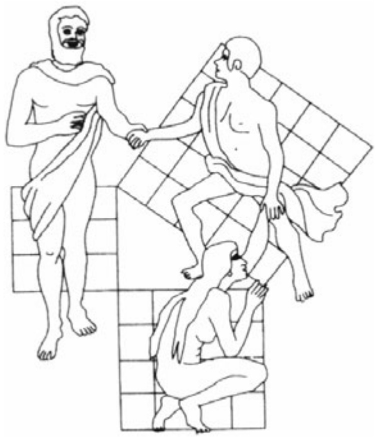

Fig. 3. The myth of Isis, Osiris and Horus. This representation of the Pythagorean theorem is attributed to Euclid

Attention is drawn to the sides of the triangle which, when endowed with the lengths of the perfect or sacred triangle (3 or 4 units), represented the mythical union of Osiris (god of the dead and of fertility) and Isis mother of Horus, the god who unified upper and lower Egypt.[10] According to the legend, the triangle having sides 3, 4 and 5 is linked to the proof of Pythagoras' theorem. The area of the square built on the hypotenuse, 5 units in length, represented by Horus the child in the myth, is obtained as the sum of the areas of the squares on the other sides. This icon is, for Plato, the symbol of marital union (fig. 3).[11]

Applying algebraic knowledge to Euclid's theorems the master masons were able to calculate the geometry of the pyramid (fig. 4).[12] From the direct and indirect formulas the relationship between the apothem of a side and that of the square base could be obtained. For certain values this was shown to be equal to the square of the height of the volume.[13] For the height h of the pyramid and the half side of the base a, one obtains:

$$h \times a = h'^2 \,.$$

Applying Pythagoras theorem, the following expression is obtained:

$$h \times a = h^2 + a^2 \,.$$

Having divided by a the problem is reduced to the second degree equation previously used to calculate Phidias's mean, which is about

$$\left(\frac{h}{a}\right)^2 - \left(\frac{h}{a}\right) - 1 = 0 \,,$$

an expression that calculates the golden ratio as a positive solution of the equation which coincides as shown with

$$x^2 - x - 1 = 0 \,,$$

that is,

$$\Phi^2 - \Phi - 1 = 0 \,.$$

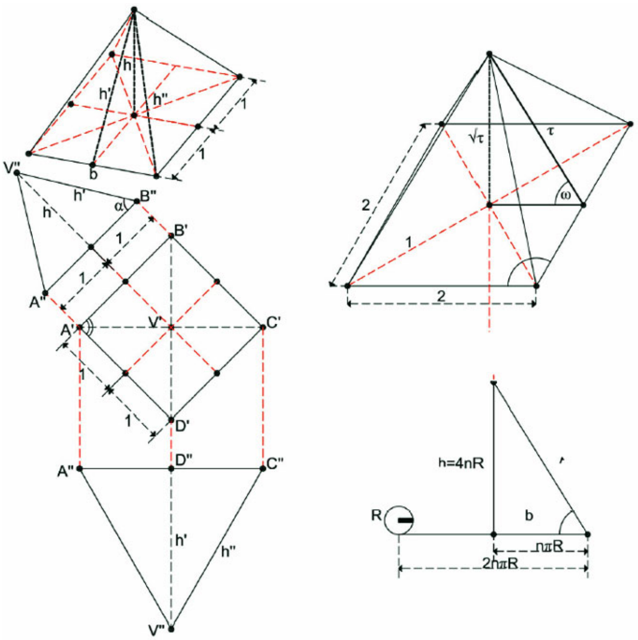

Fig. 4. The geometry of the "Egyptian" pyramid. Re-elaboration in CAD by A. Erario

Whether or not the craftsman responsible for building walls was able to compute and solve the problems encountered during work in progress was a very debated issue at the beginning of the twentieth century.

Amongst the documents that attest to the craftsmen's technical expertise one can undoubtedly include Villard de Honnencourt's *Livre de portraiture* [1235]. Villard was a master mason who, like all of his colleagues in the profession, had travelled to wherever work could be found.

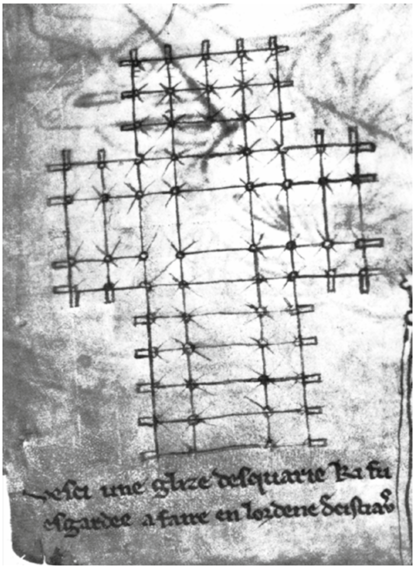

Fig. 5. Plan of a Cistercian church from the sketchbook of Villard de Honnecourt, fol. 14v.

The booklet, considered by some a construction site or guild book [Frankl 1960: 36], by others a *Carnet de voyage*, travel book [Barnes 1989: 211], or a long pondered work is generally thought to be "an exceptional testimony" [Erlande-Branderburg 1987: 9] on the art of building walls and the technical jargon of cathedral building [Bechmann 1993: 313-314]. Confirmation of this is given by figure shown on fol. 14v in which the Latin cross plan of a church is described: *Vesci une glize d'esquarie, ki fu esgardée a faire en l'ordene de Cistiaus* (Here is a church with a square plan, which it was thought to build for the Cistercian order) says the caption [Villard de Honnecourt 2009: 93] (fig. 5).

The drawing in the perspective of the work carried out by the school of Roland Bechmann (1880-1968) is a guide in the composition of series of vault spans. Just as eloquent is the drawing on fol. 18v included amongst the pages dedicated to geometrical research drawing where a 'squared' face is represented (fig. 6).

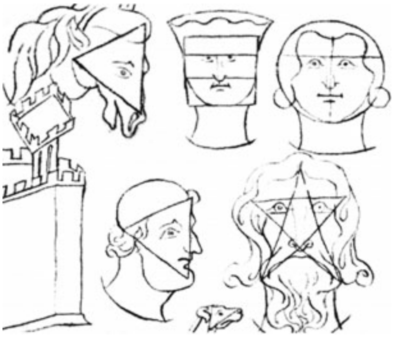

Fig. 6a. Geometric schemes for designing figures, from the sketchbook of Villard de Honnecourt, fol. 18v (detail)

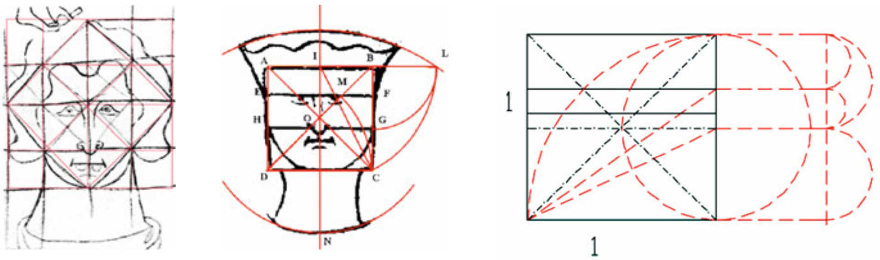

Fig. 6b. left) sketch from the sketchbook of Villard de Honnecourt, fol. 19v; centre and right) graphic reconstruction on a face drawn by Villard (fol. 18v) of the method given by Vitruvius for drawing the human face according to classical proportions, after [Tani 2002].

The apparently naïve structure teaches those who have the means to understand how to divide a segment in mean and extreme ratio (Euclid, *Elements*, Bk. II, prop. XI). An alternative way to divide a given segment into proportional parts which has endured the test of time for its aesthetic qualities is the "Golden number" for dividing lengths according to Matyla C. Ghyka's definition ("golden section") [1931] (fig. 7).

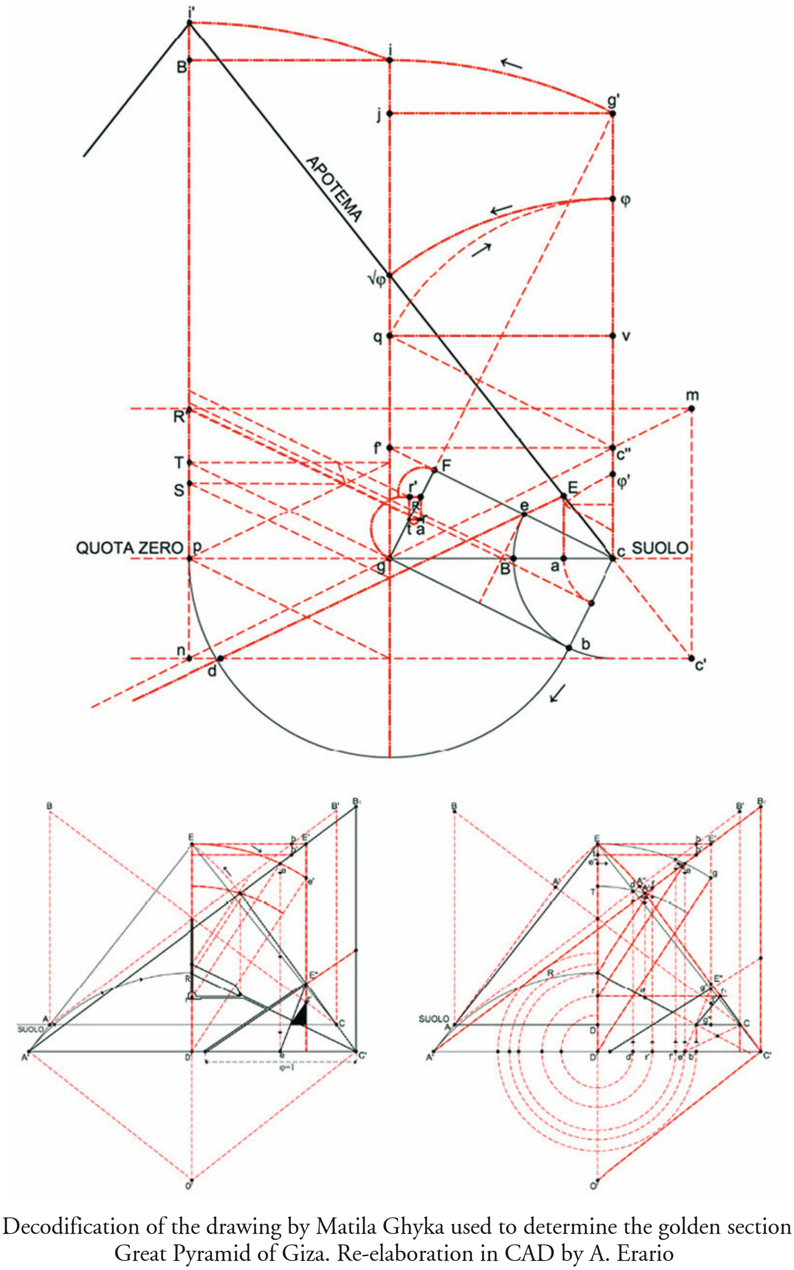

Fig. 7. Decodification of the drawing by Matila Ghyka used to determine the golden section in the Great Pyramid of Giza. Re-elaboration in CAD by A. Erario

The need to find in buildings ratios and proportions which were functionally and statically correct and as well as aesthetically pleasing can also be seen in the properties of the basic shapes obtained using pairs of plumb bobs. Villard de Honnecourt adopts as a model for cloister passage ways a circle between an inscribed square and a circumscribed circle: "In this way one obtains a cloister that has the same surface area as the lawn" (*Par chu fait om on clostre autretant es voies com el prael*) as the caption of figure 20r says. The drawing tends to hint at, rather than display, the geometric configuration, if one is to give credit to the page titles concerning the *Ars geometrie* in which it is placed. In this perspective the subsequent drawing is also quite revealing: a rhombus inscribed in a square bisected by the medians and diagonals, which is the oldest of known icons and which bears the caption: "how to divide a stone so that the two halves are square" *(Par chu partis om one pirre que les moitiés sont quareies* (fig. 8).

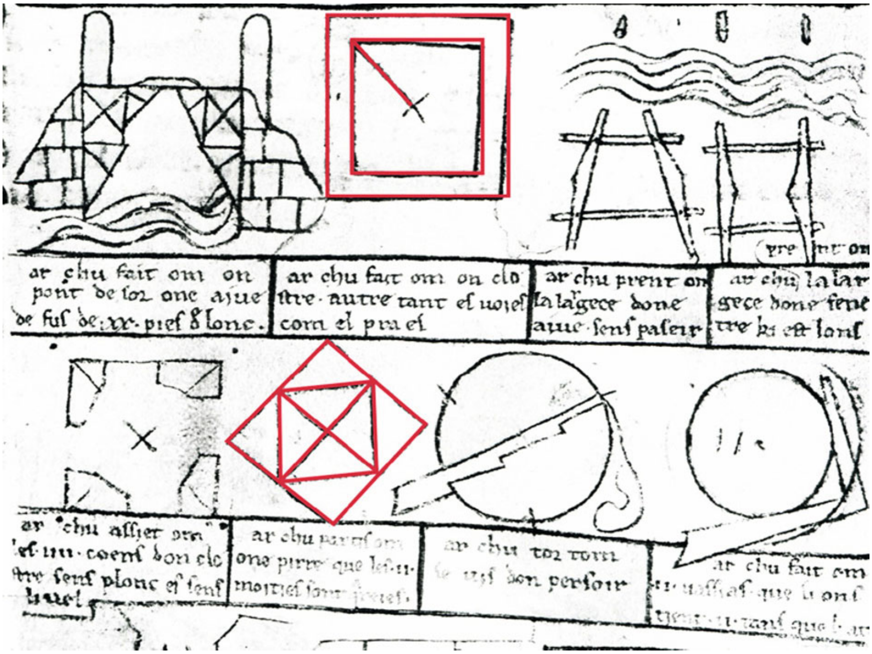

Fig. 8. Villard de Honnecourt, fol. 20r (detail). Above) *Par chu fait om on clostre autretant es voies com el prae* (By this [means] one makes a cloister equal in it walkways as in its garth); Below) *Par chu partis om one pirre que les IJ. moitiés sont quareies* (By this [means] one divides one stone [so] that the two halves are square). See [Villard de Honnecourt 2009: 136]

The figure shows the easiest and fastest way to halve and double areas in a set perimeter, a problem tackled by Plato in his dialogues, who cited Eratosthenes (276-194 B.C.). In order to save the city from the plague the oracle of Delos had ordered the altar of his temple to be "doubled", the Athenians made a mistake and "octupled" the cube that served as a sacrifical altar.[14] The main point of the anecdote mentioned by Plato, i.e., the importance of geometric logic, is also made in the dialogue between Socrates and Meno, who, under the master's guidance, learns how to calculate the length of the side and the diagonal of a square (Plato, *Meno*, 84d-85b). In the introduction to Book IX Vitruvius refers to Plato as the inventor of methods for laying out enclosures, angles and distances on the ground (fig. 9).

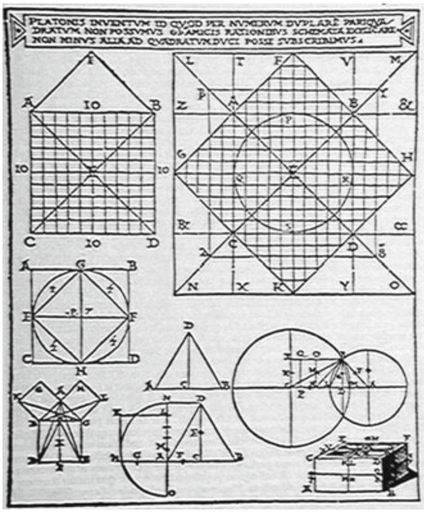

Fig. 9. Cesare Cesariano, methods for doubling the square
[Vitruvius1521: Liber Nonus, CXXXXIIIIr]

Compared to the drawings that illustrate the content, the exegesis behind the decoding of the Vitruvian text is a more significant example of how mathematical thought evolved in time. If one considers the secrets unveiled in the table included in Roriczer's *Büchlein von der Fialen Gerechtigkeit* (*Booklet Concerning Pinnacle Correctitude*) [1486], the metamorphosis started when on the building site the reduction of masonry sections was checked on the basis of the height from the ground (fig. 10).

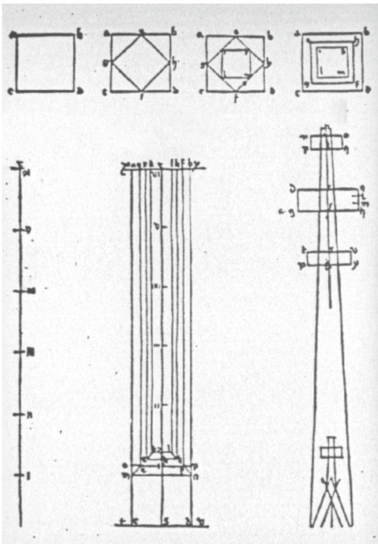

Fig. 10. Plate from Mathis Roriczer, *Büchlein von der Fialen Gerechtigkeit* [1486]

For those who are familiar with descriptive geometry, the construction unveiled by Mathis Roriczer and Hans Schmuttermayer (1435-1495) with the permission of the authorities, when the new guild interests had already arisen, betrays the homology correspondences (in particular homothety)[15] that are established between a horizontal plane and a vertical plane leaving fixed the modular relationships between plans and elevations [Borsi 1967]. A useful choice from a figurative point of view as well as can be seen by drawing the geometrical matrixes of the mapping points or by re-tracing the color pattern of the marble tiles [Mandelli 1983: 116-117]. The possibility that there might be some technical content allegorically hidden in the *Livre de portraiture* is supported by information concerning its author.

According to some of Villard's biographers, it is possible that he started his apprenticeship by studying the texts that were in the Honnecourt-sur-Escaut abbey, which was the epicentre of several schools or similar structures in the area [Tani 2002]. Le Goff identified about twenty-two such schools [Bechmann 1993: 17; see also Le Goff 1993].

However, not all scholars consider Villard de Honnecourt a learned man. According to James Ackerman he, was "not an architect or master mason, but an artison with more limited capacities" [Ackerman 2002: 34]. In the American scholar's opinion the vertical section of Reims cathedral, the one that appears on fol. 32v of the *Sketchbook* (fig. 11), cannot be a 'real life' drawing because at the time the cathedral had not reached its final height, but that it is "conceptually highly sophisticated" compared to the other drawings collected in his notes [Ackerman 2002: 36].

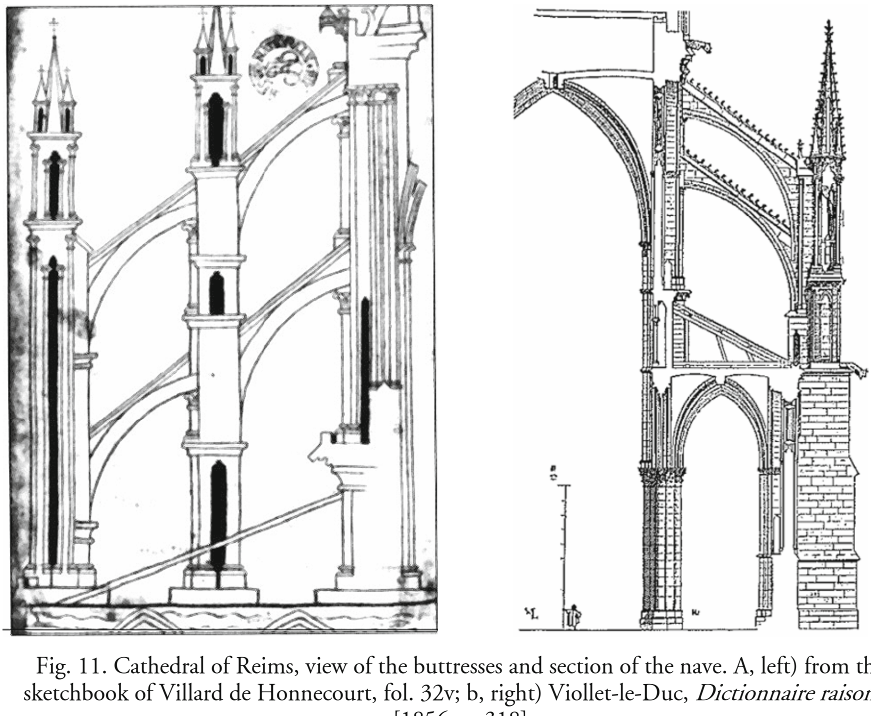

Fig. 11. Cathedral of Reims, view of the buttresses and section of the nave. A, left) from the sketchbook of Villard de Honnecourt, fol. 32v; b, right) Viollet-le-Duc, *Dictionnaire raisonné* [1856, p. 318]

The possibility that the sketchbook might include sketches by different authors was considered also by Ronald Bechmann's disciples: this hypothesis however does not in any way alter the value of the sketchbook. What James Ackerman found of particular interest is "the demonstration of the capacity to represent on one plane cuts at several levels" [Ackerman 2002: 40].

A new figure emerged: that of the a different kind of master mason who could draw and interpret designs who used the workshop where he kept his scale drawings, engraved on a plaster covered floor [Lenza 2002: 60-61]. The need to show or to see what the end product would look like before it was actually built brought about the refinement of a drawing system from which the professional figure of the architect emerged.

In great building works it is customary to have a main master who manages and conducts the work by word only and rarely – or perhaps never – actually performs any practical task. It was a situation that the construction site workers resented, as one can easily understand: "The masters of the masons, carrying a baguette and gloves … worked not at all, although they received a larger payment; it is this way with many modern prelates" [Gimpel 1961: 136]. Borsi described the rise of a new professional figure: "Nothing could be further from the truth than speaking of the choral nature of the Gothic cathedral; the opposite is true, a single mind directed the work … and thought of everything" [Borsi 1965: 45 (my translation)]. It is in the pre-Renaissance period, claims Le Goff, that the art of building becomes a science and the architect a scientist [Le Goff 1981: 235].

The times were just right for Brunelleschi to prepare for his countrymen, on the door of Santa Maria del Fiore, an application which made it possible to describe the spatiality of objects starting from two-dimensional points of view, It would take two centuries for the biunivocal procedures to develop into a complex disciplinary corpus around which design know-how would evolve, a science in continuous evolution in direct correlation with the metamorphosis of ideas [Docci and Migliari 1996: 9-11].

Notes

1. See [Viollet-le-Duc, 1854-1868, Tome VII, Proportion, sub voce]: *On doit entendre par proportions, les rapports entre le tout et les parties, rapports logiques, nécessaires, et tels qu'ils satisfassent en même temps la raison et les yeux. À plus forte raison, doit-on établir une distinction entre les proportions et les dimensions. Les dimensions indiquent simplement des hauteurs, largeurs et surfaces, tandis que les proportions sont les rapports relatifs entre ces parties suivant une loi. «L'idée de proportion, dit M. Quatremère de Quincy dans son Dictionnaire d'Architecture (Tomo II, p.318), renferme celle de rapports fixes, nécessaires, et constamment les mêmes, et réciproques entre des parties qui ont une fin déterminée». Le célèbre académicien nous paraît ne pas saisir ici complètement la valeur du mot proportion. Les proportions, en architecture, n'impliquent nullement des rapports fixes, constamment les mêmes entre des parties qui auraient une fin déterminée, mais au contraire des rapports variables, en vue d'obtenir une échelle harmonique.*
2. *Praeterea, veritas est adaequatio rei et intellectus. Sed haec adaequatio non potest esse nisi in intellectu. Ergo nec veritas est nisi in intellectu* (Truth is the conformity of thing and intellect. But since this conformity can be only in the intellect, truth is only in the intellect) [Thomas Aquinas, *Quaestiones disputatae de veritate* q. 1, a. 2, s.c. 2].
3. Leonardo Pisano, *Liber Abaci,* 1202: *Nouem Figure indorum he sunt. Cum his itaque nouem figures, et cum hoc signo 0, quod arabice zephirum appellatur, scribitur quilibet numerus, ut inferius demonstratur* (The nine Indian figures are: 9 8 7 6 5 4 3 2 1. With these nine figures and with the sign 0, which the Arabs call zephir, any number whatsoever is written, as is demonstrated below) [Leonardo Pisano 2002: 17].
4. See [Bagni 1996, vol. I]. The separation of geometrical science and mathematical science is ascribed to the distinctions introduced by Archytas.

5. There were also other translations available, such as the one by Cicero, but our knowledge of it is indirect and fragmentary.
6. Porphyry of Tyre, commentary on *Ptolemy's Harmonics* (*Eis ta Harmonika Ptolemaiou hypomnēma*) [Camerano: Capo. 1, http://www.pitagorismo.it/?p=157].
7. Eudemus of Rhodes, *Physica*, fr. 30 (see also Simplicius, *On Aristotle's Physics* 4, 67, 26).
8. The series was obtained as an answer to the following question: "How many pairs of rabbits can be produced from a pair in a year if it is supposed that every month each pair begets a new pair which from the second month on becomes productive?"
9. From the history of mathematics we know that the Egyptians knew how to trace a right triangle by using a rope divided into twelve equal parts.
10. "The upright, therefore, may be likened to the male, the base to the female, and the hypotenuse to the child of both, and so Osiris [the father] may be regarded as the origin, Isis [the mother] as the recipient, and Horus [the son] as perfected result. Three is the first perfect odd number: four is a square whose side is the even number two; but five is in some ways like to its father, and in some ways like to its mother, being made up of three and two" [Plutarch 1936: 136-137].
11. The geometrical demonstration seems to be ascribed to Euclid, it is certain, however, that Plato chose it as an emblem of his Republic; see Plato, *Republic* VIII, 546.
12. The isosceles triangle has the following property: the angle opposite the base is a 90° angle. It can therefore be obtained by inscribing it in a semi-circumference. The properties of an equilateral triangle are referred to the entire circumference . The median point of the triangle is in relation to the circumference and therefore can be traced to the calculation of the mean of Phidias.
13. The height of the pyramid is equal to the tangent line of the acute angle formed with the base. For $\varpi = 54°54'$ hypotenuse $\phi \cong 1.618$.
14. In a letter addressed to Ptolemy III, cited seven hundred later by Eutocius, in his commentary on Archimedes' *On the sphere and cylinder* Eratosthenes told the King that the legendary Minos wished to build a tomb for Glaucus in the shape of a cube. In a different context the same problem is posed and linked to Plato's the famous sentence "Let no one ignorant of geometry enter".
15. Homothety a linear transformation that involves no rotation, the composition of a translation and a central dilatation. It is of the form $x' = kx$, $y' = ky$, and is a stretching if $k > 1$, and a shrinking if $0 < k < 1$ [quoted from http://www.maplesoft.com/support/help/AddOns/view.aspx?path=Definition/homothety].

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About the author

Adriana Rossi received her degree in architecture with honors from the University of Naples Federico II. She was qualified as an architect in 1985. That same year she began to collaborate with the University of Naples in the department of "Configurazione e attuazione dell'architettura". She earned her Ph.D. in 1992 in "Survey and representation of built work", and was awarded a post-doctoral grant from the Dipartimento di Rappresentazione of the University of Palermo. She joined the Second University of Naples as a researcher in 1995, becoming part of the Department of "Cultura del Progetto" in 1996. Today she is an Associate Professor there, teaching "Drawing and techniques for design". Among the books she has authored are *I Campi Flegrei* (Officina Edizioni, 2006), *DisegnoDesign* (Officina Edizioni, reprinted in 2008) and *Suoni di pietra* (Deputació de Barcellona, 2009).