MOMENTS OF PERFECTION

A Study of Natural Lighting in the Church of Santo Spirito.

by Laura Ellen Wyckoff
B.S. in Management
Boston University 1979

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Architecture at the Massachusetts Institute of Technology
February 1984

© Laura E. Wyckoff 1984

The Author hereby grants to M.I.T. permission to reproduce and to distribute publicly copies of this thesis document in whole or in part.

Signature of Author:

Department of Architecture
January 20, 1984

Certified by:

Lawrence B. Anderson
Thesis Supervisor
Dean Emeritus of the School of Architecture and Planning

Accepted by:

Chester Sprague, Associate Professor
Chairperson Departmental Committee for Graduate Students
Abstract

Reliance on natural lighting in the Renaissance is put into context through the exploration of religious light symbolism and the explanation of the dependence on the solar path to measure the passage of time.

Through systematic observation of the light distribution throughout the year 'moments of perfection' are identified. These are the times when the natural reinforces both the formal religious function and powerful geometry of the church.

This thesis concludes that Filippo Brunelleschi used precise calculations with great deliberateness to manipulate light placement in the design of the church of Santo Spirito. This church is not an isolated incident but rather part of a larger, unexplored body of knowledge.
ACKNOWLEDGEMENTS

My sincerest thanks to,

My advisor, Lawrence B. Anderson

professors, Harvey J. Bryan
Kurt W. Forster
Henry A. Millon
John R. Myer

friends, Denise Garcia
Roland Malamuceanu
Josiah Stevenson
Anna Wu
Jeff Yates

and family
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>9</td>
</tr>
<tr>
<td>I. CONTEXT</td>
<td></td>
</tr>
<tr>
<td>The Movement of the Sun</td>
<td>19</td>
</tr>
<tr>
<td>The Symbolism of the Sun</td>
<td>41</td>
</tr>
<tr>
<td>Geometry of the Sun: Applications</td>
<td>63</td>
</tr>
<tr>
<td>Filippo Brunelleschi: Applying the Principles</td>
<td>79</td>
</tr>
<tr>
<td>II. THE EXPERIMENT</td>
<td>93</td>
</tr>
<tr>
<td>Technique Description Documentation</td>
<td></td>
</tr>
<tr>
<td>III. ANALYSIS</td>
<td></td>
</tr>
<tr>
<td>The Proportions of the Church and the Placement of the Windows</td>
<td>131</td>
</tr>
<tr>
<td>A Moment of Perfection</td>
<td>141</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>153</td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>1. Chronology</td>
<td>157</td>
</tr>
<tr>
<td>2. Previous Studies</td>
<td>158</td>
</tr>
<tr>
<td>3. Temporal Hours</td>
<td>163</td>
</tr>
<tr>
<td>4. Solar Geometry in Plan</td>
<td>165</td>
</tr>
<tr>
<td>SELECTED BIBLIOGRAPHY</td>
<td>167</td>
</tr>
</tbody>
</table>
INTRODUCTION

All the evidence gathered so far points to the conclusion that Renaissance architects like Brunelleschi and Michelangelo used precise calculations with great deliberateness to manipulate daylight in the churches they designed. This study puts into context and decodes the manner in which natural lighting had been used to enhance the religious experience during the Renaissance.

To begin to understand the meaning of this aspect of the religious experience one must consider the value placed on light during the Renaissance. There are two levels of interpretation which will be taken into account: The first is to examine the symbolization of the sun, which has been manifested directly into religious worship in both ancient civilizations and more modern times. The second level is literally the time and direction keeping information provided by the predictable solar path. These two properties are intermixed and incorporated into all cultural value systems. Just as today we can scientifically explain the passage of time and the rotation of the Earth, in the Renaissance the Church performed this function. The relationship can be described as such.

SUN—\\rightarrow \text{CHURCH}—\text{TIME}
The first section establishes the basis and context from this cultural point of view.

In order to decode this system of meaning one must identify the precise lighting effects. The second section includes specific information about the placement of light beams throughout the year for one particular church.

This entire section will focus on the church of Santo Spirito in Florence, Italy. The church of Santo Santo was designed by Filippo Brunelleschi in 1436. The church is a breath taking example of an architecture created with a close adherence to a strict proportional system. Within the church of Santo Spirito the only element breaking the symmetry is the long light beams originating from the clerestory windows. Considering the distinction of the church as an architectural monument, incorporating the purest Renaissance principles, it is a perfect example to begin exploration.(Appendix 1 provides a brief biography of Brunelleschi and a listing of the major events in Florence during this period)

The study is directed towards certain key events which are called "i momenti perfetti." These moments of perfection occur when the
manipulation of natural light reinforce the formal religious function of the church to produce dramatic and startling effects. These "moments of perfection" were first observed at the summer solstice in Florence. On this day both the morning and evening mass begins as the light beams are centered on the arches in the nave and choir. (The photographs were taken at these two times.)

It is hypothesized that the placement of light beams on particular days was used as criteria in the determination of the proportions of the church and in the selection of the window height and position. In the Renaissance this system of lighting would have had value and meaning. The last section illustrates how these lighting decisions could have been made and discusses the interpretation of a pious person viewing these phenomena.

Because of previous evidence gathered it is hypothesized that the logic of light movement in the church of Santo Spirito is not an isolated instance, but rather it is part of a larger body of knowledge. It is believed that this information was passed on orally because of sacred associations with light and therefore has remained undocumented. More modern analysis of these churches seems to have been done from the formalistic point of
view, which tends not to consider the issue of lighting. Only through systematic study of the placement of light beams as they operate today, can these criteria be evaluated. The exploration of the church of Santo Spirito is a point of departure. (Appendix 2 is an explanation of previous study done)

Decoding this integral system for making design decisions will not only add to our perception and understanding of these specific monuments, but re-aquaint architects today with one of the most powerful design tools, natural light.
CONTEXT


THE MOVEMENT OF
THE SUN

"By its essential nature the clock dissociated time from human events." Lewis Mumford

With the acquisition of the capability of tracking time, our society has shifted from measurement by natural cycles to the precision of mechanical regulators. Our daily life experience has subsequently become removed from natural biological rhythms and moved closer in shape and texture to the more complex rational ordering of the clock\(^1\). The precision afforded by the clock goes hand-in-hand with the accuracy required for our commercially regulated economy and rationally ordered production. Like the printing press, the refinement in the measure of time has had an enormous impact on all of our social systems\(^2\).

Before the advent of the clock, human methods for reckoning the passage of time were via co-existence with the natural cycles of the sun. Each culture has had a specific notion of time according to its understanding of its place in the universe\(^3\). This interpretation applied both to daily existence and cosmic comprehension. In order to understand the use of light by the Catholic Church, one must understand how sun movement was inescapably linked to overall human comprehension of the
world. The beliefs and values that this understanding entailed subsequently came under the direction and control of the Catholic Church.

Every early civilization has had to have a system by which its members could understand their existence in relationship to the passage of time and the movement of the cosmos. Universally this systematization has been dependent on the interpretation of the natural cycles. The time from sunrise to sundown measured the working day, the full moon marked the length of a month and as the sun would begin to ascend in the sky it signalled the beginning of a new year. It is here that all cultural assumptions have their roots.

The way we experience the passage and measurement of time can be divided into two levels: The first is on the personal level, involving daily routine and the scheduling of everyday events. The second is on the lifetime level and involves the comprehension of one's place in the larger scheme of things. The important point to realize is that though these two concepts are severed for our every day life they were experienced as linked at the beginning of all civilizations. One must make an attempt at sympathetic imagination to realize that until recent historical times people
4. IBID p.11.
didn't have scientific understanding, clocks, or artificial illumination. They were therefore far more dependent, and vulnerable, and also more aware of natural cycles than we are today. The passage of time and the understanding of the universe were intimately linked for human beings trying to understand their place in the world. With the internalization of the passage of time came a certain kind of understanding of one's place in the universe.

"The essential function of religion is to overcome the threat of annihilation and anxiety of the present by assimilating profane man within the infinite process of the sacred cosmos." (4) While all early civilizations had their roots in the deification of natural phenomena, Christianity absorbed these values and re-explained natural cycles to suit its own conception of God.

Christianity, one might say in short, is one attempt to define human existence in relationship to natural cycles. The value system it developed was intimately tied to the daily and yearly movement of the sun. Therefore the path of the sun, which is the most direct record of the passage of time, is given profound religious implications which manifest

THE CALENDAR

The yearly implication of the movement of the sun can be identified in the calendar. Earliest civilizations believed that the movement of heavenly bodies were instruments which affected everyday happenings on Earth.(5) The earliest calendars we know often served magical and astrological ends. It was supposed that certain planets exercised power at particular times of year; the year was accordingly divided in response. Under such systems, the calendar has more religious than scientific purpose and function.

With the coming of Christianity the conception of the calendar changed. Time was no longer deified; rather it was a creation of God. As stated by Augustine, “God, whose eternity uttered not, created the world in time, the world was made in time, not with time.”(6) Thus changed the conception of time from cyclical to developmental and subsequently the role of measuring time (which was a creation of God) fell into the hands of the Church.

of the Church.

The calendar, as defined by the Church, refers to the list of saints' days and feast days which are to be observed through religious rite. "Religious rite" refers to acts of worship intended to celebrate the glory of God and the salvation of men and women. The source for all Catholic worship is Christ's own act of worship, his sacrifice at the cross. This act was the once-and-for-all times truly unique act of worship. The practice of Catholicism is based on this sacrifice in the Mass of Easter. All other historical elements of worship can be interpreted and set as it pleases the pope, as long as they don't interfere with the essential nature of the religion as dogmatically defined.

The evolution of the calendar has been based on a mixture of carry-over traditions from the astrological calendar of the Roman empire, with papal interpretations of worship. The measure of the week is an arbitrary assignment which comes from the ancient study of astronomy. The seven days are named after planets and pagan gods: "Monday" refers to "moon day;" from Wotan comes "Wednesday" and from Thor comes "Thursday;" "Saturday;" is "saturn day;" and "Sunday" is obviously "sun day;"
9 IBID p.220.
One day per week is obligatory day of worship: This of course is Sunday; the symbol of divine light being the sun.

Easter, the most important festival is dated according to the Jewish calendar based on lunar rather than solar cycles. Easter is always the Sunday following the first full moon after the spring equinox. Though the date changes every year, it always falls around the time of year when the length of the day equals the length of the night, the equinox. The lighting conditions could be considered similar for the small deviation of days.

Christmas, on the other hand, occurs after the time of year when the sun reaches its low point, the winter solstice. At the time of Christmas the sun had begun to ascend in its path through the sky. Since the real birth date of Christ is not known this feast was set arbitrarily. It is believed that this time was chosen as a Christian counterpart to the Roman celebration of the re-birth of the sun.

Other structures imposed by the Church included a list of stations throughout the year. Stations were particular churches which were attended for particular solemn masses on appointed days. These services were led
10. In Studies in Early Roman Liturgy on p.16 there is a listing of the earliest saints' days with a brief explanation of the order they were introduced. A modern list can be found in the Penguin Dictionary of Saints.
by the pope and attended by parish priests. They were supplemented by saints' days and festival days which also were tied to specific dates and churches. (10)

In short, through the definition of the rite of worship the Church demarcated the passing of a year. It is suggested that just as earlier civilizations used the calendar directly according to seasonal changes, these values are likewise incorporated into Catholic worship. This integration serves two purposes: First, for a pagan it would have been easier to accept a Christianity that came complete with celebrations complementary to the system of beliefs it replaced, as opposed to embracing a completely novel and different system. Second, the observable natural phenomena would support the new religious interpretations, heightening their creditability. This was possible because pope had complete authority to explain the relationship between natural phenomena and religious beliefs that people struggled to comprehend.

DAY TO DAY

On a day to day basis all civilizations relied most heavily on the sunpath to describe and define the parameters of the day. At the earliest stages, the day would be defined by sunrise, noon, and sunset, followed
from the Canterbury Tales ca 1390:

It was four o'clock according to my guess,
Since eleven feet, a little more or less,
My shadow at the time did fall,
Considering that I myself am 6 feet tall.


typically soon after by smaller divisions and refinements. Before artificial illumination, all people were sensitized to both the movement of the sun and the phases of the moon for regulating their lives. In Roman times a typical fool who received an invitation to come to dinner "when the shadow was 12 feet long" is represented as mistaking this to mean shadow due to the moon, arriving consequently after sunrise, with apologies for being perhaps late.(11)

The earliest devices for the measurement of time appeared in Egypt as early as 1500 B.C.. These were the first sundials, indicating the hour by the shadow cast by the sun. Sundials, by their nature, are a "philosophical tool which combines the two poles of the human condition most faithfully: transience and arrogance-transience in the ephemeral nature of the shadow cast and arrogance in the use of gyrations of the Earth around its stupendous luminary delicately to define successive quanta of human existence."(12) As an instrument the sundial is complete, in that the dial uses natural cycles to measure the passage of time. It is a beautiful expression of both scales of comprehension of time.

By 290 B.C., there were sundials in Rome. These sundials were
from Naccius Plautus, a Roman comic, ca 250-184 B.C.

"The gods confound the man who first found out
How to distinguish hours! Confound him, too,
Who in this place set up a sun-dial,
To cut and hack my days so wretchedly
Into small portions. When I was a boy,
My belly was my sundial; One more sure,
truer, and more exact then any of them.
This Dial told me when it was proper time
To go to dinner, when I aught to eat.
But now a days, why, even when I have,
I can't fall-to, unless the sun gives leave.
The town is so full of the
confounded dials,
The greatest part of its inhabitants,
Shrunken up with hunger, creep along the streets."

13. from Derek da Solla Price in Technology and Culture, Vol. 1, No. 1, 1964 "it would be a mistake to suppose that...sundials...had the primary utilitarian purpose of telling time. Doubtless they were on occasion made to serve this practical end, but on the whole their design and intention seems to have been the aesthetic or religious satisfaction derived from making a device to simulate the heavens. Greek and Roman sundials, for example, seldom have their hour lines numbered but almost invariably the equator and tropical lines are modelled on their surfaces and suitably inscribed. The design is a mathematical tour-de-force in elegantly mapping the heavenly vault."

Movement of the Sun

placed in public squares around the city. Because of the nature of the
sundial the specific function is not clear: These sundials, it is speculated,
are both measuring the passage of time and mapping the movement within
the cosmos, for these could be one and the same thing.(13)

From Vitruvius we have the only description of the construction
of the sundial. In his Ten Books of Architecture, he explains how to make
a sundial, and listed thirteen types of dials already in existence. Vitruvius
expresses regret that he could not invent a new type, "for they all have
been made."

With the coming of Christianity the Church took over the
function of regulating time. There were two ways to understand the hour:
According to Dante the Church, like the Bible, used temporal hours.
Temporal hours (as compared to equal hours) vary according to the time of
year. According to this system the amount of time between sunrise and
sundown and between sundown and sunrise, are divided by 12. On the
spring equinox day and night are equal and have equal hours. (Appendix 3)
However during the year the duration of an hour varies from season to
season.(14)
noon mark inscribed on the exterior of the church

15. Chris Morgan, "From Sundial to Atomic Clock", in The Book of Time.

16. Sundials by Arthur Green is the account of a study that was made of medieval these dials. The author claims his most significant finding to be the fact that the scratched lines seem to always be placed at 15 degree intervals.
By order of Pope Gregory 1 in 600 A.D., sundials were to be placed on the exterior of all churches. (15) At the time, churches were the major public institution and the keeping of time was a cultural function. Churches which lacked a sundial often had instead what is known as a noon mark. (see photo) This is a line inscribed on the exterior of the church which would mark the cast shadow of a gnomon at noon, when the sun was due south.

Another variation of this timekeeping system was used by many Anglo-Saxon communities and called a "mass-clock." A mass-clock is a dial inscribed on the exterior of a church whose markings were believed to coincide with the position of the shadow cast by a gnomon at the time of the mass. (16) A famous example is the Straussberg Munster dial which has six divisions. These divisions indicate the canonical hours: *hora prima, hora tertia, hora sexta, hora nona, hora vespera, and the completorium.*

By the time of the Renaissance, the Catholic Church had assumed full responsibility for the tracking of time. Measuring time required the full attention of at least two monks in each order. The monks would ring bells at the time of the mass during the daytime hours. During the night hours
The cover of treatise by Welper explaining the construction of the sundial. The illustration depicts types of sundials commonly used.


18. It wasn't until Welper published his Treatise in 1625 that this information was made public.
the monks would monitor the hours by the stars, water clock, or the recital of a particular psalm which required a set length of time to be recited. (17) Though there were other methods to measure time, during the Renaissance the sundial was supreme. Sundials were constructed in every conceivable form and were considered art objects worthy of presentation to a king. Diallists were considered specialists and kept their methods of construction secret. (18)

It was the Church that performed the scientific function, as we know it, of measuring time. By associating the natural phenomenon of the passing of time with the religious institution of the Church is a further indication of how the Renaissance value system was structured. Through education, the population learned to gauge the passing of the day by the conventional markers of religious rite. Because the conception of time was explained by the Catholic Church, and furthermore regulated by the Church itself, it seems most likely that time was by definition based on religious rite. Upon seeing the position of the sun in the sky a person would think in terms of a relationship to a religious belief. In this manner the Catholic Church was able to strengthen the beliefs of its adherents by keeping close links to the natural cycles.
THE SYMBOLISM OF THE SUN

The study and understanding of the movement of the sun was a vehicle for men and women to understand recurrent cycles of events in daily life, but also the sun itself was an important symbol of perfection, guidance, and divinity for all civilizations. Based upon speculation of which ideas would have influenced either Brunelleschi or the monks of the church of Santo Spirito, one may cite examine philosophers whose attitudes about symbolism of the sun are expressed clearly in their own writings. This representation of the human relationship to the sun during the Renaissance will aid in the understanding of what a religious person would have thought and felt when seeing direct light beams in the church of Santo Spirito.
1. As defined by the *New Catholic Encyclopedia*: Augustianism, "represents an attempt to reach an ever fuller understanding of revealed truth through supernatural graces and gifts aided by the principles of philosophical inquiry."

The church of Santo Spirito is a Catholic church of the Augustinian sect. Augustinianism is a particular philosophy, including theological doctrines, identified with the order of Saint Augustine. Key theological positions described in the writings of Saint Augustine will aid in the interpretation of light beams in its place or worship.

Aurelius Augustine was born in 354 in North Africa and prepared by education for a lifetime of teaching. Augustine was sent first to Rome and then to Milan where he came in contact with the teachings of Saint Ambrose. Augustine had been seeking a personal philosophy of life, and the encounter with Saint Ambrose caused Augustine internal conflict. He had to choose either honors, wealth, and marriage or a holy life dedicated to God. On Easter 387 he was baptized. Augustine returned to Africa where he was ordained priest in 391, and then chosen bishop of Hippo in 396. As bishop of Hippo, Augustine led a strict rule with preachings every Sunday and Feast days. The ideas of Saint Augustine are well preserved in the one hundred thirteen book, two hundred letters, and five hundred sermons he left behind. Augustine's views about the symbolism of both light and numbers will be focused on.

An important basis for all the writings of St. Augustine is his well developed theory of signs. Considering many possibilities Augustine outlines different types of signs and the process by which the signs are interpreted through the different senses by man. The basic notion on which his theory rests is that all things, including words, are both signs and symbols. Were a person not to perceive the message of a sign it would be his or her own fault. Therefore, these signs should be studied and understood by all receivers. Augustine’s theory was specific enough to aid in the understanding of the use of the words in the Holy Scriptures, yet at the same time it was general enough to include the signs of nature such as the sun.(3)

Sharing the neoplatonic view that it was the light rather than the sun that was the highest principle of the visible world, Augustine called Christ “the Light.” Upon this premise he explained his theory of Divine Illumination. Augustine explains that it is the Light which enlightens man. He clarifies that it is the Divine Light that allows us to gain access to knowledge. This knowledge is made up of a source of ideas and a group of impressed notions.(4) In other words it is Christ, who is the Light, who
5. City of God by Augustine included in this conception is the pseudo-Dionysius idea of Celestial Hierarchy. This theory explains that the creation can be described as an act of illumination; the beings (angels, men, rocks) emerge in hierarchy corresponding to their amount of light.
enables men and women to understand the universe. Saint Augustine found many Biblical references which would both support his notion of Divine illumination and suggest that it is the luminosity that is the measure of the splendor of a being.(5)

According to this measure of splendor Augustine understood the sun to be a symbol of the most splendid of beings and its luminosity to represent Divine Light. Knowing that Augustine perceived his role to be one of an interpreter, uncovering the messages inherent in all signs he would consider daylight to be Divine Light, and place special importance on its symbolism. Therefore for Saint Augustine the focusing of light beams on the altar of a church would both signify the wisdom of the teachings of God and convey this message to the faithful. The same message would be disclosed as the beams illuminated the various angels and saints represented in the church. This symbolization would have been passed on to Augustianian spiritualism in the fifteenth century.

Not only were antique ideas about Good and the sun accepted by Augustine; he also shared a fascination with the structural unity established by numbers and their relationships. Studying theories of Pythagorus and

7. *Da Musica* by Augustine. He also explains that some proportions are more perfect than others with the 1:1 direct correspondence being the most perfect. As always Augustine supports his arguments with Biblical references, "Thou hast ordered all things in measure, number and weight," *Wis 11:20*. 
Plato, Augustine re-iterated their ideas, adding to them interpretations of religious man. According to Augustine: (6)

"Numerical ratios are but the echoes of the perfection of God, in music these ratios are audible, in architecture they are visible." Augustine explains that "through contemplation of the visible configuration of architecture the mind is led from proportion to number and from number to the idea of God." (7)

In short, Saint Augustine is outlining a course for the comprehension of God through the rules of mathematical symbols. This form of architectural expression was rediscovered and applied to church architecture in the Renaissance. Saint Augustine's clear explanation of the religious significance of harmonic proportions was key to the re-application of ancient concepts in the sacred architecture of the Renaissance. With its rigidly defined systems of harmonic proportions, the church of Santo Spirito is an architecture of visible numerical relationships.

In conclusion one must note two points: Firstly, Saint Augustine occupies an unusual position as the incorporator of Platonism into Christianity. Since he also has opinions about visual signs, further investigation of his writings would be productive.

The second point is that the church, as created by Brunelleschi
would be a very comprehensible environment for the Augustianian believers, and their minds would leap quickly to the realization of the perfection of God. Especially in this frame of mind, experiencing the powerful "moments of perfection" would be sure to evoke a spiritual response in these pious people. The Augustianians of Santo Spirito must have had a religious system of symbolization to understand the divine light of perfection in their architecture of perfection.

DANTE ALIGHIERI

In the more than two hundred solar references in the Divine Comedy the sun can be interpreted to have many different meanings. Two points suggest that it is its co-existence which is fundamental to the religious experience of the 14th and 15th centuries.

Firstly Dante symbolizes the sun as being both a sensible sun and a spiritual sun. The spiritual sun refers to the Light of the learned: The souls in the Divine Comedy are described as Light. The sensible sun is the light of the visible sun which orients man in time and place. Dante is in

2 Purgatory, XIII, verse 16.
agreement with Platonic-Augustine tradition as he says that the sun is not only Good but the Light which illuminates the path between the light of the pilgrim (sensible) and truth (spiritual). (1)

These two meanings get intermixed and overlaid in many different ways. An example of symbolization of both spiritual and visible sun is expressed by Virgil in Purgatory:

"O sweet light by trust on which I enter this new road, do thou guide us," he said, "with the guidance that is needful in this place."

"Thou givest warmth to the world, and shinest upon it unless other reason urge the contrary, the beams must always be our guide." (2)

Virgil is not only proclaiming his love of and faith in God and His Holy Light, but also stating that His light will guide him through his eternal journey. Though he is speaking of visible light, he signifies spiritual light. This example represents the very subtle distinctions between types of symbolism in the Divine Comedy.

Inherent in this worship of the good Light of God is the acceptance of the fact that the movement of the sun itself is a reference

point, literally, of global significance. By knowing the movement of the sun, a traveler will always be able to determine his place in the world. Dante had a very precise understanding of the sun which literally guides the traveler. For example as Dante and Virgil are beginning to climb the mountains of Purgatory he says:

_The sun which is rising will show you the easiest way to climb the mountain._[3]

In short, using this exact knowledge of the sun and its movements, Dante guides the travelers on their long journey while meanwhile overlaying the spiritual significance of God of which the sun and its light are symbols.

The second major point is that within this solar symbolization, Dante uses the movement of the sun to express the divisions of the day.[4] Rather than stating numerical values in many instances he uses the office of the Catholic Church to indicate the passage of time. Dante directly connects the position of the sun to the divisions of the day, according to the rites of the Church. For Dante, the day is cyclic through the formal worship of God. According to Dante the divisions of the day are as follows:
5. Convivo. IV. XXIII. 50 to end.
<table>
<thead>
<tr>
<th>Period</th>
<th>Hour</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tierce</td>
<td>to the end of the 3rd hour</td>
<td>6am to 9am</td>
</tr>
<tr>
<td>Sext</td>
<td>4th hour to the end of the 6th hour</td>
<td>9am to 12</td>
</tr>
<tr>
<td>Nones</td>
<td>7th hour to the end of the 9th hour</td>
<td>12 to 3pm</td>
</tr>
<tr>
<td>Vespers</td>
<td>10th hour to sunset</td>
<td>3pm to 6pm</td>
</tr>
</tbody>
</table>

Dante also explained that there are offices held at mid-tierce (7:30), the end of tierce (9:00), the beginning of Vespers (3:00), and mid-vesper(4:30).(5)

There are three instances in which the day is described in association with the mass of the 14th century Church. All of them imply the equivalence of the position of the sun and the office of the Church.

In the Inferno, Dante, while struggling to leave is told,

"Get up on your feet," said my master
"the road is long and the path rough and already the sun has returned to mid-tierce."(6)

Mid-tierce is the hour described in Convivo as 7:30 and is an hour of office.
7. Purgatory, III. 25-26 In the Divine Comedy human beings cast shadows while spirits do not. The presence of a cast shadow is a way of differentiating one from the other. For example Purgatory III 98-96 “When those in front saw the light broken on the ground at my right side, and my shadow falling on the bank. They stopped and drew back a little and all the others who came after them, not knowing why, did the same. “Without your asking, I declare to you that this is a human body that your see by which the sun’s light is broken.”

The next instance is as Virgil and Dante are getting ready to climb the mountain of Purgatory. Virgil says:

"tis Vespers there already where is buried the body with which I cast a shadow,"(7)

Virgil is saying that it is 3:00 in Italy and is 6am in Purgatory.

The third of the three examples is also as Virgil and Dante climb the mountain of Purgatory. It is afternoon as the two are rounding the third ring. Dante says:

now appeared to be left the sun's course;
   it was Vespers there
   and midnight here.

   and the rays were striking us full in the face,
     since in circling the mountain,
     we were now going to the west.(8)

Dante has skipped back to Florence for the narration of this passage. Not only is it the time of Vespers but in this situation Dante is also describing a religious experience fundamental to his Catholic beliefs. Dante is explaining how the Divine Light of God illuminated his face precisely at the moment of Vespers. It is a recollection of an encounter of enlightenment which made his trip up the mountain of Purgatory easier. The position of
the sun in the sky is a symbol of the perfect moment of Vespers and the illumination of the sun a symbol of enlightenment. Clearly Dante understood the "moments of perfection," and mass relationship to them, in the movement of the sun.

Dante is expressing the relationship to the sun that which all 14th and 15th century Florentines shared. For them the divisions of the day, instrumented through the Church, were one and the same with the cyclic movements of the sun. The sun is a symbol of God and his Divine Light. Naturally a basic component of the worship and study of God is the understanding of his Light. Thus for any religious person the sun is not a numerical representation of an hour, but rather a signal for religious events. Any pious person would look at the sun, think of God, and perform the appropriate religious observances.
Geometry is the connection between sun movement and sun symbolism. A reason the sun has been such a powerful organizing element is because of its very dependable and predictable cycles. The Earth completes one rotation on its axis once a day and makes one revolution around the sun per year. For the purpose at hand the sun will be discussed as if it revolved around the Earth, as the ancients believed.

The path of the sun in the sky changes on a daily basis at a regular rate. The sun reaches its highest point on the summer solstice, June 21 and its lowest noon point on the winter solstice, December 21. (Figure 1) It may be noted that the position of the sun for one particular hour can be described by a line connecting the points for the different days.

Today, the position of the sun for all times of year is plotted graphically on what is called a sun path chart. (Figure 2) From this chart one can determine both the altitude and azimuth for any time of year. The altitude is on the vertical axis and the azimuth is on the horizontal axis. The Earth itself is divided into twenty-four 15 degree segments or time zones, the sun moves 15 degrees for every hour. As the path of the sun varies for different latitudes so does the sun path chart. Using this type of
measurement anyone can determine the geometric relationship of the sun to
the Earth at any given point.\(^{(1)}\)

Of course this chart is a modern invention and in the 15th
century methods of calculation were much different. In the Renaissance the
astrological information was interpreted directly from the sun and the
changing length of the shadow cast. This body of knowledge is known as
gnomonics or sundialling. By tracing a shadow Renaissance man was able to
interpret information about the world in which he lived. The previous
chapters explain how the sundial has had the dual function of both
describing the heavens and recording the passage of time. The simplicity of
this notion highlights how it could easily have been applied to the planning
of the church of Santo Spirito.

The first step to make a sundial is to locate true south. This
operation is done by plotting the shadow cast by a gnomon throughout the
day. To begin with a circle of any radius would be traced with the style at
its center over which the path of the shadow would be superimposed. The
path of the sun is always a hyperbola. The hyperbola would intersect the
circle at two points. All a person need do is to connect the two points
Figure 3

1. The declination is the value assigned to the imperfections in the orbit of the Earth. The spring equinox is the only day when the declination is equal to zero. The apparent declination of the sun accounts for the difference in time between true time and mean constant time. Civilizations as far back as the ancients were aware of this deviation.

with a line and then pass a perpendicular line through the gnomon to locate true south. (2) (Figure 3)

Using the south line one could determine the latitude of the place by once again observing the shadow length. To do so a board would be erected perpendicular to a horizontal surface placed on the north-south meridian. At true noon the board will cast a shadow, of its minimum length, on the meridian line. This will define a triangle with angle “h” solvable using simple geometry. The angle “h” is the sun height. The complement of this angle plus the declination of the sun equals the latitude. (3) (Figure 4)

Because the diallists of the Renaissance kept their methods secret their precise method for plotting the hour lines is not known. However to illustrate the simplicity of the process consider a method as presented by Welper in his 1625 treatise on gnomonics. Knowing the north-south meridian, the latitude, and possessing an equatorial dial was all it took to make a dial. The equatorial dial is merely a circle divided in 15 degree segments in accordance with the twenty-four 15 degree time segments. (Figure 5) Welper explains that placing the dial at the angle equal to the latitude with 12 noon on the meridian is all one needs to do to describe the hour
The case of Santo Spirito is slightly different in that the opening for the light is not placed on the angle of the latitude, thus some correction is necessary. However controlling the precise calculations would also have been an easy task using the geometry of perspective, of which Brunelleschi has been called the inventor.

**PERSPECTIVE**

A perspective is constructed by choosing a vanishing point and then radiating lines at equal intervals. Using this system one can delineate a grid for the measurement of an object. (Figure 7) The similarity of this construction to the construction of hour lines of the sundial can easily be observed. (Figure 8)

Both systems rely on the converging of lines, placed at equal intervals, to a single point. For both the sundial and a perspective drawing a person depends on the open side of the grid to obtain the desired information. In a perspective drawing the open side of the grid is the picture plane or the image being depicted. On a sundial it is the open side of the grid on which the sun casts a shadow.
5. Often panels representing a sequence of events will depict the group within the same frame varying the vanishing point, or moment in time.
7 cited by Wittkower from Alberti Della Pittura: "If this be sufficiently explained, we may lay down for granted the doctrine of the mathematicians, as far as may serve for our purposes, that every intersection of any triangle parallel to the base must form a new triangle proportional to the bigger one. So that objects which are proportional to each other, correspond to each other in their parts."
The essential difference between the two constructions is that the perspective demands a stationary point of view whereas the sundial depends on the changing position of the sun. Conceptually, the perspective represents one line or moment in the day. In spirit the sun is the changing vanishing point of the converging lines of the sundial. The perspective drawing, geometrically, is the representation of one single viewpoint in the changing spectrum of viewpoints included in the sundial.

In his article “Brunelleschi and Proportion in Perspective” Wittkower articulates the thinking that went into the development of perspective constructions. According to Alberti, Wittkower demonstrates that similar triangles are proportional, therefore objects which are proportional to each other also correspond to each other in their parts. He then goes on to explain the use of this logic in the development of perspective theory.

The understanding of similar triangles underlies Alberti’s statement about buildings when he says it is “manifest that every intersection of the visual pyramid parallel to to surface seen must be proportional to the latter.” Alberti is explaining that every picture plane is a similar triangle to

"Given are 4 parallel lines, each one braccia long and at equal distance of one braccia from another. Let the first line be the intersection, and the distance from the intersection to the eye be 4 braccia. The ratio of diminution can be expressed by the progression 105,84,70,60. That is to say, the ratio of the intersection (which equals the height of the object) to the first object appearing on it is 105,84, i.e. 5:4 or to put it differently, the objective height of the second object to its apparent height, but the diminution on the intersection of the first to the second object equally 70:60 or 7:6 is the ratio of the second to the third object on the intersection."
the others sharing the same vanishing point.

Wittkower illustrates these relationships with diagrams. (Figure 9) When interpreting this diagram one would see either two differently sized people at the same distance from the picture plane or the same sized people at different distances. The geometric construction can be understood as either two similar triangles or two converging lines of a perspective.

In section this relationship is represented by a drawing Wittkower made from a narration of Piero della Francesca. (8) (Figure 10) This drawing incorporates the construction of perspective with the similar triangles. Considering the point of origin of the triangle to be the viewpoint, one could use these similar triangles to determine the apparent height of an object as it recedes.

This construction, as interpreted by Wittkower also diagrams the theory of sun beam placement. The eye level is analogous to the window from which the sun enters the church. The hypotenuse of the similar triangles are the different beams calculated according to the time of year. The angle that varies is the changing angle of incidence of the sun. (Figure 11)
Since the calculation made is on a straight line, it represents the beam placement for one solar position for different times of year. The smallest triangle would represent the summer condition and the largest would be the winter condition. The perpendicular lines would enable an architect to calculate the placement of the beam on the wall at various distances from the source window. This method shows one similarity between the thinking required for perspective and light beam placement.

PYTHAGOREAN THEOREM

The exact placement of light beams in a church could easily have been predicted using the Pythagorean theorem. In the church of Santo Spirito the window would act as an aperture for the sunlight to enter the nave. By definition the window is at right angle to the horizontal surface of the floor. Therefore the sunbeam, passing through the window and reaching the floor would be the hypotenuse of a pythagorean triangle.

The height of the window and its right angle would always be constants. The two other angles of the triangle change as the sun moves Angle "a" would always be the altitude of the sun and could be determined using a sundial. (Figure 12) The three angles of all triangles add up to 180
degrees. thus angle "b" would always be the complement of angle "a". Knowing all three angles and one length any architect could have solved for lengths "B and C" placing the beams precisely.

Given: \(a^2 + b^2 = c^2\)

Sine B = \(b/a\)
Cosine B = \(c/a\)
Tangent B = \(b/c\)

To Solve for b:

B = x degrees
Tangent B = \(b/c\)
Side b = \(c \times \text{Tangent B}\)
Brunelleschi is described as the genius who brought about single-handed the new metric architecture of the Renaissance. His ideas about architectural expression of a "perfect" module quickly replaced the pre-existing Gothic style, becoming the new architecture. This new architecture strictly adhered to a system of geometric relationships of harmonic proportions. In this manner Brunelleschi was able to create the environment described by Saint Augustine as the one which would lead a man's mind directly to God.

These highly controlled environments could only have been designed by a person with a tremendous compulsion for perfection and order. The introduction of the powerful element of light, an element of key religious significance, could only have been done with the precision and control that Brunelleschi applied to all his other design endeavors. This conclusion is evident through the examination of the pre-occupations of the Architect.
Brunelleschi is often called the inventor of perspective. He has been cited as being the first one to determine mathematically the apparent decrease in size of an object as it recedes from the viewer. This must have been a great task for Filippo, not only in conception but also in execution. He surely had to have tried many alternatives and face many failures. Filippo's persistence is evidence of the value he placed on the necessity of a solution, it is the perfect example of the type of problems that fascinated him. This exercise encapsulates essential components of Brunelleschi's thinking and approach to problem solving.

Drawing a perspective implies making scenarios which are visually stable. Correct perspectives are both ordered and controlled and imply a sense of reality. With his use of converging grid lines Filippo is able to create space geometrically. His two dimensional geometric creation of space is analogous to his three dimensional delineation of space using his module. In both cases a regulated geometry of lines is the basis for the making of space. Therefore both systems are a manifestation of the same compulsion Filippo had to create unity, harmony and perfection in all his environments.
When Brunelleschi first constructed perspective drawings he was so precise as to calculate and specify a position and method for proper viewing in order to avoid any distortion.
The construction of perspective implies a viewpoint and a viewer. The fact that Brunelleschi was concerned with making true the experience of an image implies the consideration of a viewer. This fact stresses the important consideration Brunelleschi placed on the perception of the viewer in the things he created. Brunelleschi does not think of geometry in an abstracted sense but rather is always concerned with the experience of the individual, thereby creating richer environments.

Lastly, perspective is a geometric construction, as established previously, is rooted in the same principals as are the calculations of light beam movement. Just as the geometry of two dimensional representation would fascinate Filippo, the powerful geometry of nature would be even more compelling. It seems likely that only after having studied sundials, was Brunelleschi able to define "the perspective grid."

A decisive influence on the work of Brunelleschi was the architecture of antiquity. There is not a single work by Brunelleschi for which a Roman precedent could not be cited. Brunelleschi spent many years in Rome, drawing, measuring and digging up Roman ruins.
(2) Edwin Daisy Thatcher, "The Open Rooms at the termæ del Ostia," in Memoirs of the American Academy in Rome XXIV
Brunelleschi would have noticed how the Romans used exact knowledge of microclimatic conditions in the buildings they designed. Undoubtedly he would have been impressed by the many skillful manipulations of daylight in the buildings of the Roman empire.

Brunelleschi would have paid close attention to the giant inlaid marble sundial in the floor of the baths of Diocletian. This dial combines information about the hour and the cosmos. Considering his fascination with dialling, this building-size dial would have caught both his attention and imagination. He would also be able to observe how climatic considerations were key criteria in the planning stages of the Roman bath. The shape and orientation of different rooms changed according to the thermal properties desired for the function. The precisely calculated relationship that these baths had to the movement of the sun are inseparable from the study of these structures. Brunelleschi would have payed close attention to the natural lighting criteria involved.

Filippo would have definitely measured and studied the Pantheon. He was probably able to observe that the powerful movement of light through the oculus is keyed to seasonal observances, illuminating appropriate
According to Vasari:

"Filippo interested himself in the Christian Scriptures and never failed to be present at the dispute and teachings of learned persons."

"Filippo studied Dante familiarizing himself with the localities measurements, and often quoting the poet in his arguments."
sections of the building at appointed times of the year. Having experienced the power of the effects of natural light, Brunelleschi would certainly have decided to manipulate the same variable in the buildings he would design.

One can conclude that Brunelleschi had both observed the effects of natural light on the planning stages of buildings and was aware of the magnitude of possibilities designing with light provided. However an weighty issue is the fact that he would be designing for a religious society and his manipulations would require precise control of the symbolism implied.

Among the tasks that Brunelleschi undertook as a distinguished architect of Florence was the design of the support devices for the staging of religious drama of the church or, sacre rapprentazioni. These are religious festivals which took place inside of four Florentine churches in conjunction with an esslesiastical visit or judgement. Sacre rapprentazioni were complex re-enactments of aspects of Catholicism, intended to reinforce a view of the religion.

For these occasions machinery would be permanently installed in the church which would enable characters to seem to fly amid lights and
According to Maestro Paolo Toscanelli, astrologer:

"when he heard Filippo argue he thought he was listening to a new Saint Paul....He was a mathematician and a geometrician. He was interested in the works of Dante and understood him well indeed."
fireworks. These festivals are described as being both exciting and dangerous. The church of Santo Spirito was one of four churches stages these events. The original church of Santo Spirito was burnt as a result of one of these performances because afterwards, “the performance was over, those in charge of the festival went off without a thought of the danger of the fire, so that at the fifth hour of the night in the top part of the tower the apparatus fire broke out and, before anyone noticed, shot so high that the flames set light to the roof of the church.”

The Augustianian involvement and Brunelleschi's participation, imply a common predilection to use of the visualization of religious events in order to reinforce Christianity. The manipulation of light beams inside the Catholic church is closely related to this way of thinking and would be a logical act for both parties involved. The two instances involve controlling an event by taking it out of the comprehension of the untrained mind and allowing it to be understood by its observer as religious. The purpose of which in both cases would be to strengthen Christianity.
From Mariano di Jacopo Taccola recorded from a speech by Brunelleschi himself:

"Do not share your inventions with many, share them only with few who understand and love the sciences. To disclose too much of one's inventions and achievements is one and the same thing as to give up the fruits of one's ingenuities. Many are ready, when listening to the inventor, to belittle and deny his achievements, so that he will no longer be heard in honorable places, but after some months or a year they will use the inventor's words, in speech or writing or design. They boldly call themselves the inventors of the things that they first considered and attribute the glory of another to themselves. There is also the great big ingenious fellow who, having heard of some innovation or invention never known before, will find the inventor and his idea most surprising and ridiculous. He tells him: Go away, do me the favor and say no such thing any more-you will be esteemed a beast. Therefore the gifts given to us by God must not be relinquished to those who speak ill of them and who are moved by envy or ignorance. We must do that which wise men esteem to be the wisdom of the strong and ingenious."
In conclusion, Filippo understood the mathematics of the powerful movement of the sun. While in Rome he would have experienced specific effects. Because of his own personal belief he would have recognized the religious symbolization of light and would have wanted to use it to increase popular support of Christianity. His own description of the necessity for secrecy aids in the understanding of why he himself never disclosed his ideas concerning light in religious architecture. Therefore when given the opportunity to design a church, he would have paid the utmost care and precision to the placement of the symbol of God, Light.
THE EXPERIMENT
THE EXPERIMENT

The study of lighting in the church of Santo Spirito was triggered by on-site observations while in Florence. The necessary task has been to establish that a direct relationship exists between natural light placement and the various times during the liturgical year. This would in turn establish intention on the part of the Architect. The previous sections framed a context for the interpretation of the natural light in the church. This section will consider the specific case of the church of Santo Spirito and present the variations in lighting effects as existing today.

In the planning stages Brunelleschi had wanted the church to face a piazza along the Arno River. This proposal was rejected because the inhabitants did not want their homes torn down, his second choice was the accepted. Brunelleschi is supposed to have chosen this orientation because of its adjacency to the pre-existing church of Santo Spirito.

The axis of the church of Santo Spirito is oriented 26.5 degrees clockwise from the north-south meridian. The facade faces towards the southwest into the piazza of Santo Spirito. On the east side there is an open lot now used for parking and on the west side there is a cloister. The majority of the windows in the church face east or west so the
Plan of the church
The church would receive both morning and afternoon light without any obstructions. In the morning there are beams which pass through the east facing windows. In the afternoon the opposite situation occurs. For the Architect to have manipulated the natural lighting the selection of the orientation would have been a key variable implying directly the direction of light in the church.

The other important variable for controlling the natural light is the selection and placement of windows and their different sizes. The lighting scheme would have to have been carefully selected and the position of each window calculated precisely. In the church of Santo Spirito the general lighting level is high. The church seems bright without large disparities in the brightness of different areas. It can be observed that the dome seems brighter than the nave while the side aisles seem darker. This is a function of the amount of windows and the heights of the respective spaces.

There are two classes of windows in the church of Santo Spirito, circular and round-headed rectangular. The circular variety will be considered first. These are used in two sizes in the church. There is one
Section through the nave of the church
large window above the doorway in the main facade and small round windows in the main crossing of the dome. The large window above the entry has been filled in with stained glass thus light does not pass through it and its effects will not be considered.

The small round windows of the dome are evenly set between thick moldings which remain flush to the interior and exterior surface. Since the moldings do not intrude into the space there would be no shadow perceived by the viewer looking up. The lighting effects of these windows would be to provide both indirect and direct light according to the position of the sun. However because of the deep cornice above the window on the exterior of the church there would be some shading. Between April and August from 11 to 1 o'clock the cornice would block the direct light from these windows.

The second class of windows are long rectangular windows of the proportion of 3.5 to 1. The uppermost portion is a semi-circle on top of three stacked squares. This window comes in three sizes and has three different functions and locations in the church. The smallest version is in the lantern of the dome. This window serves to diffusely light the dome.
Interior elevation of the nave of the church
The medium size version is placed in the center of each semi-circular chapel. This window is only one-third glazed, the bottom third is stone. Currently in the church of Santo Spirito these windows are both blocked by paintings and covered with curtains nullifying the lighting effect.

The third and biggest version are the clerestory windows located above each arch in the main space. It is from these windows which pass the major light beams. This study will concentrate on these windows and the variety of effects they instrument.
Model Set Up for Testing
THE TECHNIQUE

Before understanding the implications of natural light placement, one would have to establish the range of possible locations throughout the year. Since this investigation has been conducted over a four month period in Cambridge, MA a particular method of analysis was devised. The procedure chosen was to do a direct simulation of the natural light movement.

This simulation was done using a model, suntilt table, sunpath chart and slide projector. Using the sun path chart one could determine the angle of incidence of the sun for any time of day or year in the latitude of Florence. By attaching the model to the suntilt table with a slide projector thirty feet away one could simulate the sunpath for all times of day. Tests consisted of observing and documenting directly from the model. All time measurement was made using a sundial. The hours on the sundial are given in equal hour solar time. This is equivalent to local apparent time which differs from clock time by as much as one and one half hours during the summer in Florence. (Appendix 3)

This study isolates the morning effects of the windows on the east side of the church. The west windows, in most cases, would only
provide light later in the afternoon and its effects will not be considered. In particular this study will focus on the second window on the east side of the church for two reasons: Firstly, the second window passes over the bays which a person would see immediately when entering the church, therefore having a special impact. Secondly, because the thickness of the church would cut off light to the first window this second window is the first window of the church to have unobstructed light all through-out the year.
The Equinox

Summer solstice
DESCRIPTION

For a basis of comparison of the seasonal variety in the light paths through the church of Santo Spirito three days have been examined. These are the winter solstice, summer solstice and the equinox. The solstices are the longest and shortest days of the year and the equinox is the day when the length of the day equals the length of the night. During the Renaissance the people had clear understanding of the solar path on these days and subsequently they served as important milestones to indicate the time of the year. Dante used the equinox as a reference to assign a value for the three hour periods of the day, as defined by the Church. Pagans used to celebrate the re-birth of the sun on the winter solstice. Therefore, these days are key reference points for the measurement of the passing of the year.

All the drawings presented isolate the effect of one window over the length of a particular day. Because of the apparent movement of the sun, in most cases the beams do not originate from the opposite bay but are from a diagonal bay. Yet since each window is part of the same geometric order, and the rays of the sun are parallel, all the beams from the clerestory windows follow the same course. Each beam is important in
and of itself having a specific placement but each beam is also part of a sequence of beams all occupying the same relative positions.

The light beam begins its path at the highest point for their particular morning and then move across the various surfaces. When the sun is high in the summer sky, the beams move across the floor from west to east. At other times they remain on the wall and follow the south-north direction of the wall.
Light path through the church
THE SUMMER SOLSTICE

On the summer solstice the sun makes its longest path of the year, illuminating many different surfaces of the church.

On all the solar hour intervals the beams are positioned directly on either the end points of a bay or on the stone paving which traces the module of the bay on the floor. On this day the stone paving on the floor is an exact solar indicator at this time of year.

Follow the path of the sun as it enters the nave facade at 7:00. By 7:30, or mid-tierce, the sunlight enters from due east and bisects the arch. On 8:00 the beam is in the chapel and moves across to meet the stone paving at precisely 9:00 (sext). At 10:00 the light spot is bisected by the stone paving of the column line. This beam moves to the cross paving where it once again aligns with the stone paving at the mid-point of a perfect solar hour. The path ends as the light beam disappears when striking the center line of the church at 11:00 o’clock.
The Summer Solstice
Light path through the church
The equinox is the day when temporal hours, which vary according to the length of the day, are equivalent to our own system of equal hours. Each hour is measured by one 1/12th of the total movement of the sun for this day.

Beginning at sunrise for each solar hour the beam is placed either on the column line or the imaginary line bisecting each arch. The beam makes its way over one bay every two hours.

Only on this day does the sunlight enter the church from the east position at 6:00 AM. This early morning beam shines into the building and then directly out of the window of the diagonal bay.

Upon re-entering the church the beam travels 10 degrees meeting the column line directly on top of the dark moldings at precisely 7:00. By 8:00 the sun has moved another 12 degrees and the light beam has passed over one-half bay. At this moment the light beam illuminates the opposite bay perfectly bisecting the space between the arch and the window. This is the only day that any of these events occur.
The Equinox
Light path through the church
Since the winter solstice is the shortest day of the year it has the shortest solar path. This short path marks the northern most edge of the path of the beam from the one window.

The light path has its beginnings and end points on the column and bay center points. As on the other two days the solar hours align perfectly with the grid lines of the church.

Because the sun remains low in the sky on this day the light path never enters the bay opposite the source window. As the beam finishes its path at 11:00 the beam is the closest along the wall it will ever be to the front of the church, leaving behind three unlit bays.

A special allowance was made in the representation of the sunpath. On the winter solstice there would not be a complete path from the first window because of the obstruction created by the thickness of the facade. Were it accurately presented in this drawing the path of this window would not exist. However because the drawing only depicts three bays the full path of the second window would also not be shown. Therefore this drawing is the combination of the path of the second window superimposed on the position corresponding to the first window.
The path of one window over the year

Winter solstice

The Equinox

Summer solstice
THE THREE DAYS

These different days of the year are best understood in comparison to one another. This chart is a combination of the light paths from the window in the second bay for the three astronomically significant days. All the days of the year are included between these three paths.

The shortest path, winter solstice, ends tangent to the arch while the longest path strikes four different surfaces ending in the middle of the nave floor. The ratio of these two paths in length is approximately 2:1. In between these two days is the path of the equinox. This path goes all the way down the column yet never strikes the nave floor, or conversely all the summer days between the equinoxes do strike the floor of the church.

The path of the sun for the whole year covers four bays. Each solstice point could only be hit by one window one time of year, the two bays in between would be covered twice per window. However there are many windows in sequence making the identification of the source window a consequential variable.

To best apprehend these beams over a yearly basis one should visualize the sun path beginning at its lowest longest limit, and like a wave, moving daily upwards shrinking towards its solstice path. With the
Light beams aligned with columns

Light beams aligned with center line of arches
progression of the seasons the light moves forward through the church. For each stage the light beam would have a changing relationship to one of the four bays it covers.

The thin vertical beams of light, shaped by the long windows, strengthen the division lines within the bay of the church. These light lines are close in width to the dimension of the column, intensifying both the vertical and horizontal rhythm of the section. Were the windows to be of a smaller length or a different shape this relationship would not be apparent.

When the light beam is positioned on the column line a grid of a standard width is laid over the entire elevation of the church. When the light beam is aligned with the window line the equal divisions of the height of the church is immediately visible. This shifting position of light is a constant reminder of the underlying system of proportion used to design the church.

These light lines create clear lines of progress in the church. An observer could easily use the placement of light relative to a particular line as a measurement of the stage of the year. Since the light beam from this
Winter solstice

The Equinox

Summer solstice

Hour line described by the light paths
one window covers four bays it is likely that the relationship of the light beam to one of the four bays would be a clue to the time of year and directly symbolized as such.

Abstracting the sun path information on an hourly basis is another way to analyse it. One must identify the light spot for the same hour on both solstices and then connect them with a line to construct hour lines in the church. The hour line describes the position of the light beam for that particular moment for any day of the year. With this information one could compare the lighting conditions in the church of Santo Spirito for any particular times of year. Furthermore looking at the relationship of the hour line to the astronomical days one could guesstimate both the time of day and year.

Using this system of dual coordination and a model the possibilities of direct coincidences between the church dimensions and solar intervals such as determined for these days for other days of the year. To date another day has not been identified with so many direct links between the architecture and the placement of natural light as on these astronomically significant days.
ANALYSIS
Figure 1

The Equinox
PROPORTION AND THE PLACEMENT OF THE WINDOWS

As concluded from analysis of empirical evidence, the dimension of the church of Santo Spirito has a direct relationship to the steady movement of the sun. The constant hourly movement of the sun in the sky is demarcated in the bay of the church. The integration of these lighting principles must have played an important role in the selection of the proportions of the church and the subsequent placement of the windows. It is hypothesized that the height of the windows and the proportions of the church are regulated by two different geometric systems. One can trace Brunelleschi's decision making process using the light path for any particular day. For the purposes of this study the equinox will be used. (Figure 1)

The points of departure are preconceived ideas about the design of the church. Brunelleschi knew his church would be an architecture composed of a multiplication of an equal module. He knew that the hour lines of the solar path should align directly with the mid-point and column lines of the church on this day. Brunelleschi began with a grid covering the entire site. After laying out the grid Brunelleschi considered the effect of sun movement at each specific orientation. Filippo conceptualized the grid
On this day the solar hour interval value is directly measured by one bay in the church. The first bay dimension was established by the difference between the east beam at 6:00 AM and the beam which is perpendicular to the church at 8:00 AM.
extend beyond the walls of the church allowing himself adjust the grid and evaluate different solar orientation.

Evaluations would consist of selecting a point and then testing it using the superimposition of the hour lines of the sun for the equinox.(Appendix 4) Brunelleschi would have varied the orientation of both the window and the grid and changed possible window locations. (Figure 2 and 3) These diagrams exemplify the change in effect that the orientation and window placement have on the placement of light beams. After many of these trials, Brunelleschi would have been able to make a decision.

Brunelleschi found that it is the proportion of nave to bay of 2:1, when the windows are located on center, which best suited his specifications.(Figure 4) Brunelleschi was able to fix his orientation and choose which ever size he felt appropriate for the particular church. At an orientation of 26.5 degrees west of the north-south axis Brunelleschi could assign a two hour value to each bay. (1) This lighting effect would remain constant regardless of the size of the church as long as the absolute proportions remained the same.

The next phase of the planning of the church was the design of
Figure 5

Lines regulation the section
the section. This involved defining the heights of spaces and ordering the elements within. In this case the placement of the window is a critical variable. To fix the window height Brunelleschi would have had to consider the exact position on the wall which he intended the beam to illuminate at appointed moments.

Brunelleschi began the construction of the section with the same regulating line grid he established in the plan. (Figures 5 and 6) He used this system of dimension to locate column capitals, moldings and the heights of the arches. One must note that the window placement is not part of this system, rather windows are placed according to a logic of its own. The height of the window approximates the size of the bay on the diagonal.

Brunelleschi intended that the equinox, being the day of equality between the day and the night, be the day that the sun should finish its path on the bottom of the column, rather than entering the nave at 11:00. Filippo intended that on the days when the length of the day exceeded the length of the night that the beams should enter the mainspace. While on the days that the length of the night exceeded the length of the day the
Figure 7
beams would remain on the wall or in the chapels. The relationship of the beam to the nave of the church is a solar indicator of the time of year. These calculations were made using precise knowledge of the Pythagorean theorem.

Brunelleschi visualized the light beam to be the hypotenuse of a right triangle. (Figure 7) He realized that the angle opposite the wall would be equal to the sun height at that particular time. Measuring his plan of the church he knew the distance from the window base to the column to be 20.8 meters, solving for x;

\[
\text{Tangent 43 degrees} = \frac{9325}{20.8} = \frac{19.3}{x}
\]

Brunelleschi could check his initial figure of 20.8 using the Pythagorean theorem \(a^2 + b^2 = c^2\). (Figure 8)

Side a = 2 units of 6.5 or 13 Side b = 2 1/2 units of 6.5 or 16.25
Brunelleschi determined the window height in the church after he set the proportional relationship of the grid. The window height could be established in absolute values and would be adjusted proportionally to the size of the church.

In this manner Brunelleschi was able to integrate his ideas about natural lighting into his vision of architectural space. He simultaneously worked with the geometry of the sun and the formal geometry of the grid, creating a system of perfectly complementing geometries.
A MOMENT OF PERFECTION

Labels are applied to the times of year when the natural light beam bisects the arches on the west wall of the nave, "moments of perfection." These events are "moments of perfection" in the practice and ritual of Catholicism.

This study concentrates on the second window in the second bay for two reasons. Firstly, the window in the front bay does not complete its entire course because the sunlight is cut off by the facade. Secondly, the back portion of the church is the first portion of the church that a person would see upon entering. Therefore it is hypothesized that this section would have the most immediate impact. The beams from this one window would bisect four different arches during the year. (Figure 1) Since each bay of the church has a window, each light path must be considered as part of this series of windows. Even though one window shines on four bays this path is repeated by all windows so the church is not a collection of lit and unlit bays. The user must mentally connect the source window to the beam to understand the light movement. In the instance of the second bay its path would not be followed by another beam for most of the year.
Both the arch itself and the group of four arches served by a single window may have held special symbolism in the Renaissance. This conclusion derives from a passage by Dante in the "Convivo."

Therefore, inasmuch as our life, as has been said, and also the life of every living thing here below is caused by the heaven, and the heaven reveals itself to all such like effects not by the completed circle of its revolution, but by a portion of it; it follows that the initial movement of the life must be upwards; and as the heaven, like an arch mounting up and then turning back, controls all lives (I say controls the lives both of men and of all other living things), they needs must, as it were, assimilated to the likeness of an arch. Returning, therefore, to human life only, which is our present concern, I affirm that it goes on its way, after the likeness of an arch, mounting up and then descending. ..........

"The arch indeed is not only designated in writings by reference to its middle point; but is divided into four parts corresponding to the four combinations of the contrary qualities which enter into our composition. To these combinations, I mean, to each in turn, one part of our term of life seems to be appropriated, and these parts are called four ages. The first is Adolescence, which is appropriated to warm and moist; the second is Youth, which is appropriated warm and dry; the third is old age, which is appropriate to cold and dry; the fourth is Decline, which is appropriated to cold and moist, as Albert writes in the fourth book of the Meteora."
And these stages are likewise found in the year, in Spring, Summer, Autumn, and Winter. So too in the day, that is, up to Tierce, and later up to None, leaving Sext between these parts for a reason that is easily apprehended, and afterwards up to Vespers and from Vespers onward. And therefore the heathen say that the chariot of the sun had four horses; the first they called Eous, the second Pyroeis, the third Aethon, the fourth Phlegon, as Ovid writes in the second book of the Metamorphoses, concerning the parts of the day.” (1)

This passage suggests that the grouping of four arches in the church of Santo Spirito is embedded with this same symbolism. Over a yearly period the movement of light through the four bays would symbolize the terms of life and the change of seasons. The daily movement of light over a single arch would have its own individual symbolism. The "moment of perfection" when each different bay is bisected, will be examined each moment being distinct instances which have particular implications.

On the summer solstice the beam from window two would bisect arch one at mid-tierce. In other words at this unique time of year the morning office is signaled by the centering of the light beams from the east. The solstice would be an appropriate time of year for this harmony for two reasons.
The first is the mere fact that in the Renaissance the solstice was an important astronomic milestone. Being in synchronization with the natural cycles on these easily identifiable days would be a reassuring sign to the church goers that all is in order in the heavens. These "moments of perfection" would be a symbol of God's presence to a pious person during worship.

Another reason is that the Feast Day of the Patron Saint of Florence, San Giovanni, is only three days away from the summer solstice, thereby sharing the same lighting effect. The Feast Day of San Giovanni is one of the largest celebrations during the year in Florence and has a well attended mass. Once again being in harmony with natural cycles would be a clear indication that their Patron Saint is near by.

At the other end of the range arch four is bisected at mid-sext (10:30) on the winter solstice. (Figure 3) The winter solstice is only days away from Christmas and would have the same lighting effect. Thus the light beams would key special mass held only at this particular time of year.

In its path from solstice to solstice the light would travel over two bays. Bay two would be bisected on approximately April 21 and
August 21 at 8:30. Bay three would be bisected on approximately October 21 and February 21 at 9:30. The religious significances of these days has been investigated.

It is hypothesized that in the church of Santo Spirito the feast day of Saint Augustine would be an important celebration because of the emphasis on his teachings in their practice of Catholicism. This day is August 28 and would have the same effect as August 21 with bay two bisected at 8:30. Almost every day in the calendar is a Catholic feast day. A clear method of discriminating what would have been important to Augustianian worship has yet to be established.

In summation the hour difference in time between the moments of perfection in the four bay series is one equal hour each. These three hours add up to the three hour allocation of time by the church to a particular period of the day (tierce; 6–9, sect; 9–12). Nested symmetrically in the two periods of the morning is an additional measure of time, the three hour yearly path of the beam from arch one to arch four.
This single moment of perfection is both a signal of the seasons and has a special relationship to particular masses during the year. Still today, in Florence both the morning and evening masses begin with this event on the summer solstice.
CONCLUSION

In the Renaissance human awareness of the movement of the sun included the knowledge of the relative changes in the position of the sun on the horizon throughout the day and year. The sun was a weighty symbol and all people aligned themselves both religiously and scientifically to the dependability of its movement. Therefore, natural light held special value and a particular role in the Catholic church.

In the church of Santo Spirito the movement of light beams from the large clerestory windows is coordinated to; religious events, the seasons, and the hour intervals. Using a symbolization of the passage of time found in the work of Dante, Brunelleschi intended the path of one window to cover the back four bays of the church, symbolizing the changing stages of life and the seasons. Within this system there are "moments of perfection" when the light beams signal the beginning of a religious function. Furthermore the light beams align with the dominant geometry of the church on key astronomically significant days.

Brunelleschi used mathematical calculations to predict the movement of light in the design stages of the church of Santo Spirito. With ancient geometry he was able to determine the appropriate proportions for the
church, the window height and the orientation to achieve this particular lighting effect.

It is hypothesized that, like many other Renaissance principles, the manipulation of natural light in the church of Santo Spirito could have its roots in Roman precedent. Brunelleschi interpreted the Roman distribution system for use by a religious society. Other Renaissance architects living after him were sure to have adapted Brunelleschi’s system of lighting as they had done with so many of his other design ideas.

The observations discussed in this study are just the tip of a much larger body of knowledge. The next step would be to document the light distribution system in other churches and graphically record the way in which natural lighting was placed in direct relationship with both architectural elements and religious symbols consistently, by other Renaissance architects. Uncovering this integral logic for making design decisions is sure to be useful to both architects and historians and aid in the deeper understanding of the Renaissance and its architecture.
APPENDIX 1
Chronology
from Filippo Brunelleschi by Eugene Battisti
selected from the chronology on pages 329-337

1377
Birth of Filippo Brunelleschi.

1388
Throughout Europe, beginning of a stern repression of popular risings.

1397
Birth of the scientist Paolo Toscanelli 28 August (feast of St. Augustine)

1400
Second contract for the Pistoia Altar, mentioning “Pippo di ser Benincasa da Firenze”

1402
In the tax levy the sons of Ser Brunellesco appear for the first time, taxed along with their father.

1405
Florence conquers Pisa.

ca. 1406
Ptolemy’s Geography translated from Greek into Latin

1410
Construction of the octagonal drum of the Cathedral dome.

1418
A public competition solicits ideas for the centering of the dome, for the scaffolding, and for the construction machinery, with a prize of 200 gold florins to anyone whose projects are accepted, as well as compensation for any expenses contracted in preparing models. Brunelleschi apparently proposes immediately a highly unusual solution.

1419
Brunelleschi is paid for further work on his dome model, having added a lantern and a circular gallery around the dome and drum. Contracts for the first foundations of the loggia of the Foundling Hospital.

1420
Brunelleschi and Ghilberti are appointed together with the capomaestro Battista d’Antonio, as supervisors of the construction of the dome. Half the foundations of the church of the Foundling Hospital are paid for.

1421
At the Foundling Hospital the first column of the loggia is put into place.

1423
War declared against Milan. Birth of Antonio di Tuccio Manetti.

1425
Brunelleschi is named Prior for the S. Giovanni quarter. It may be in connection with this appointment that he made the perspective painting of the Baptistery.
Florence suffers an extremely grave financial crisis. Many artists are impelled to seek work elsewhere.

Masaccio paints the *Trinity* in S.Maria Novella.

According to the Biographer, in this year Brunelleschi has his first contacts with a committee for the reconstruction of Santo Spirito.

Luca della Robbia begins his *cantoria* for the Cathedral.

Brunelleschi goes to Mantua at the invitation of Giovanni Francesco Gonzaga, and is called Ferrara by Nicolo III d'Este. Ghiberti and Battista d'Antonio are to make a model for the closing ring of the dome, to be shown as round or octagonal.

War against Milan. Donatello and Michelozzo go to Rome.


A committee is organized for the rebuilding of Santo Spirito.

Alberti dedicates to Brunelleschi the Italian translation of his *De pictura*. Foundations are laid on the north side of the choir of San Lorenzo. Brunelleschi submits a design for the long elevated wooden passageway to be built between S. Maria Novella and the Cathedral—across almost half the city—for the solemn pontifical procession on the occasion of the dedication of the Cathedral. "On 30 August, at the third hour, the oculus of the dome was closed and all the bells rang and the Te Deum was sung and the divine office was sung thanking God."

Cosimo de' Medici pledges to have the work resumed in S. Lorenzo at his own expense.

Formal opening of the Foundling Hospital (still unfinished).

The first monolithic column is brought to the site at Santo Spirito. Brunelleschi dies in the night of 15-16 April and is buried in Giotto's campanile.

The first column is raised at Santo Spirito.

Completed at the time of his death are the Old Sacristy and the two adjacent chapels in S. Lorenzo, and the loggia of the Foundling Hospital with the upper storey. Unfinished are the exedrae of the Cathedral, and the lantern, Santo Spirito, and San Lorenzo.
The point of departure for this exploration was conclusions drawn in the Millon/Smyth article, "Michelangelo and Saint Peters; observations on the interior of the apses." This study revealed that in the transept of the basilica of St. Peter the windows on the interior and the exterior are not aligned. The interior windows are on axis but the exterior windows are shifted to the east. The one spot in the church where the central windows would seem to be in alignment is at the altar. From this point the pope would be the only one to get an unobstructed view of the sky and therefore sense himself to be at the center of the church. Restrained by Bramante's placement of four piers Michelangelo uses the windows and lighting to regain a sense of centrality. This manipulation of light suggests that for Michelangelo light in religious architecture was more that just illumination, but a tangible element of form.

The thinking about placement of light beams, window configuration, and its implications were opened as a result of these conclusion. Investigations were begun with a study of the lighting effects in the Michelangelo proposal for the church of San Giovanni dei Fiorentini in Rome.

This study involved building a model which would isolate one window in the drum. Then using a sunpath chart one could determine the angle of incidence of the sun for any time of day or year. Tests consisted of observing and documenting the beam movement directly on the model.

It was observed that on the Feast Day of the Patron Saint the light beam would be above the altar, identifying the chapel from which mass would be said. On the winter solstice, near Christmas time, the light beams would shine on axis with the doors in two
As the early morning mass begins there is a light beam above the chapel containing the altar.

Each window is keyed by the tone of the nearby sun. Windows one, two, and three all provide direct light for the time periods listed.
DECEMBER 25th
Christmas Day

directions. Because of the predictable geometry of the sun, the light beams seemed to be keyed into seasonal observances. The study of San Giovanni dei Fiorentini has been useful in developing a methodology and beginning a train of thought.

In the summer of 1983 further investigations were conducted in Florence, Italy. Besides the church of Santo Spirito it is suspected that the baptistry of San Giovanni, San Miniato and S. Maria Novella also have calculated lighting effects. With further on-site investigation more churches are sure to be uncovered.

The sun is much lower in the sky on Christmas Day and the beams do not enter the main space. At twelve o'clock there are light beams placed on axis with the door in two directions.
Temporal versus equal hours through-out the year

<table>
<thead>
<tr>
<th>Hour</th>
<th>Equinox Time</th>
<th>Summer Solstice</th>
<th>Winter Solstice</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>4.30</td>
<td>7.30</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>5.45</td>
<td>8.15</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>7.00</td>
<td>9.00</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>8.15</td>
<td>9.45</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>9.30</td>
<td>10.30</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>10.45</td>
<td>11.15</td>
</tr>
<tr>
<td>N</td>
<td>0</td>
<td>0</td>
<td>N</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1.15</td>
<td>12.45</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>2.30</td>
<td>1.30</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3.45</td>
<td>2.15</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>5.00</td>
<td>3.00</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>6.15</td>
<td>3.45</td>
</tr>
<tr>
<td>Sunset</td>
<td>6</td>
<td>7.30</td>
<td>4.30</td>
</tr>
</tbody>
</table>

1 hour = 60 minutes
1 hour = 45 minutes
1 hour = 75 minutes
APPENDIX 3
Temporal Hours

Another way of collecting the data would have been to use the temporal system of measuring hours. The length of a temporal hour is determined by the length of the day. For example on the summer solstice when the day has 900 minutes (or 15 equal hours) each of 12 hours would be assigned 75 minutes, or 1/12th of 900. On the winter solstice when the day have 540 minutes (or 9 equal hours) each temporal hour equals 45 minutes.

Plotting these daily milestones lead to a different set of information then recorded in these drawings. In this study the decision was made to overlook this alternative system. This decision was made after marking the paths according to these values and observing that the hour relationship of the light beam was less decisive then in the equal hour system. It was also observed that the changing position of any one hour was more difficult to connect, mentally, then the equal hour intervals. Never the less, on the equinox the hour measurement would be the same, and so would the solar intervals recorded in the drawings.
The euinox

The winter solstice

The summer solstice
APPENDIX 4  
Solar geometry in plan

The equal hour intervals of time do not correspond to equal changes in the position of the sun as seen along the horizon. This value is measured by the position of the sun relative to the east and is referred to as the azimuth or bearing angle. (Figure 1)

This study incorporates this information in the calculation of light beam placement. The information was taken from the sun path chart in "Geometry of the Sun." The drawings illustrate the relationship of the movement of the sun on a grid. The three different instances are different days of the year. The variation in angles represents this change in azimuth.

The change in azimuth of the sun per hour throughout the year

<table>
<thead>
<tr>
<th>hour</th>
<th>The Equinox</th>
<th>Summer Solstice</th>
<th>Winter Solstice</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 to 12</td>
<td>20</td>
<td>36</td>
<td>15 degrees</td>
</tr>
<tr>
<td>10 to 11</td>
<td>18</td>
<td>24</td>
<td>13</td>
</tr>
<tr>
<td>9 to 10</td>
<td>16</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>8 to 9</td>
<td>14</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>7 to 8</td>
<td>12</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>6 to 7</td>
<td>10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>5 to 6</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 to 5</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SELECTED BIBLIOGRAPHY

History of Architecture


Dante Alighieri


**Religious Studies**


Sundials


The Study of Time


Chris Morgan, "From Sundials to Atomic Clock", in The Book of Time.