THE ARRANGEMENT OF THE UNIVERSE:

THE APPLICATION OF
ARCHITECTURAL METAPHOR
TO MODERN PHYSICS

by
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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

The ultimate goal of physics is to construct an accurate cosmology: to search for explanations of how the universe itself is constructed at its most fundamental level, and how this proliferates to the effects we see on a human scale and beyond. The models of the universe that physics and its predecessors have produced over the centuries have each, in their own turn, influenced our perception of how the universe functions, from Ptolemy's concentric spheres to the uncertain world of quantum mechanics.

The cosmology of how we believe the world is made affects how we arrange the world we build ourselves: how we group or organize the elements in our buildings, whether we think about objects or about voids, or the ratio and proportion of architectural features. While it is likely correlation due to a shared cultural zeitgeist and not direct causation in most cases, we can see a historical relationship between changes in dominant models of the universe and changes in architectural language. The discovery and acceptance of the heliocentric universe in the 16th and 17th centuries, for example, coincides with the increased use of ovals and other non-ideal shapes in architecture.

The revolutions of *modern* physics, since the late 19th century to the present day, have propagated into the popular consciousness and into art, but its effects on architecture are less clear. How can modern physics influence our perception of our place in the universe and the shape of architecture, and how can architecture be used to communicate the reverse?

I explore this question through the design of a museum of modern physics on Saint Mary's University campus with exhibits focusing on Einstein's theory of relativity, quantum mechanics, and two potential theories of quantum gravity, using the design of each space to investigate how what the scientific discoveries on display say about how the universe is constructed.

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1 INTRODUCTION

1.1 CONTEXT

The history of physics has shaped our cosmological worldview. Discoveries during the Scientific Revolution, such as the revolution of the Earth around the Sun, or the principle of gravity, signalled a shift from envisioning a universe that is well-ordered and organized by a hierarchy imposed from the top down, organized in layers based on how perfect the content of each layer was believed to be, to a universe whose hierarchy arises from the bottom up, from constituent parts and laws that are the same everywhere for everyone.[1]

The discoveries of modern physics, a term I used to refer to physics from the end of the nineteenth century until the present, are well outside the realm of normal human experience. The two main complementary theories of modern physics are renowned physicist Albert Einstein's theory of relativity, which applies to the behaviour of matter and space at large scales, and quantum mechanics, which applies to the behaviour of forces and matter at subatomic scales. Each has radically shaped our understanding of the world around us, not only in terms of the structure of the universe at the subatomic scale, but of the nature of space, time, energy, and matter themselves.

The work of physics does not end with these two theories. Both remain fertile areas of study. That the theories are two *separate* theories, as well, is the biggest problem in physics. The biggest question in physics, now, is how to combine or otherwise reconcile the vastly different explanations of these two theories into a single unified theory of physics that explains the behaviour of the cosmos at both impossibly large and impossibly small scales. Many theories abound, but the two most popular contenders are loop quantum gravity, which arises from the principles of relativity, and string theory, which arises from the principles of quantum mechanics.

Neither loop quantum gravity nor string theory has yet been supported by physical evidence. However, the

[1] Alexandre Koyré, *From the Closed World to the Infinite Universe*, Publications of the Institute of the History of Medicine, the Johns Hopkins University, Third series, the Hideyo Noguchi lectures, v. 7 (Baltimore London: Johns Hopkins University Press, 1957), 2.

phenomena described by relativity and quantum mechanics are unquestionably part of our daily lives, such as in the need to correct the clocks of GPS satellites to account for the effects of general relativity or the use of principles of quantum mechanics in the construction of lasers. Despite this, these phenomena are largely imperceptible without sensitive instruments. Each theory's implications for the universe are, for the non-physicist, cryptic at best and utterly ignorable at worst. They remain, however, an integral factor in shaping how we believe the world is structured.

Comparing these two disparate theories explores the startling difference in how we can conceive of the universe depending on how you look at it: smooth or made of discrete pieces, full of gravity or absent of gravity entirely, uncertain or concrete. The tensions between the two main theories of physics emphasizes that our picture of the universe remains tantalizingly incomplete, and the efforts to reconcile them foregrounds the desires to understand the structure of the world around us.

1.2 GOAL

This thesis explores how we might use architectural metaphor to allow people to experience the complex ideas of physics through the materiality and organization of architecture. How do we, as non-physicists, experience what the discoveries of physics say about the world we live in?

While the average person knows little about the details of any of these theories, the broader ideas have nevertheless become known within wider culture. There were a few physicists in the 1920s and 1930s, such as Arthur Eddington and James Jeans, wrote books about contemporary physics that were accessible to non-scientists; this helped disseminate the ideas of contemporary physics to artists of the time.[2] There are well-known physicists today who have sought to communicate the often impenetrable discipline to others: Neil deGrasse Tyson, Katie Mack, and Brian Cox, for example. Two theoretical physicists—Lee Smolin and Carlo Rovelli—have written books aimed at a non-physicist public in recent years about the yearned-for

[2] Susan Stanford Friedman, "Scaling Planetarity: *Spacetime* in the New Modernist Studies – Virginia Woolf, H.D., Hilma Af Klint, Alicja Kwade, Kathy Jetnīl-Kijiner," *Feminist Modernist Studies* 3, no. 2 (May 3, 2020): 125, https://doi.org/10.1080/24692921.2020.1794470.

unified theory of physics. These books have particularly inspired the content of this thesis.

The work of physicists uncovers information about the nature of reality that, when filtered and disseminated in a more accessible format, inspires wonder, and allows us to reconstruct our worldview into something new and different. We see the ripples of physics in pop culture, such as in the idea of parallel universes or wormholes in science fiction, or in the misuse of the word "quantum" to suggest complex science.

Painting and sculpture, too, have long been influenced by the ideas of physics. Artists such as El Lissitsky, Umberto Boccioni, and Hilma af Klint drew explicitly from ideas in contemporary physics in their work. We can see in their work an understanding of the implications of both the theory of relativity and of quantum mechanics in the way they use shape and form to suggest a reality different than the one we experience in day-to-day life. The German painter Franz Marc felt that scientific advancements regarding the structure of the atom would lead to new artistic styles that would follow in the footsteps of recent discoveries about the universe, writing:

> *"They will not be looking for this new form in the past, nor will they find it on the exterior of nature, on her facade in a conventional style. They will build the form from the inside out according to their new knowledge, which has transformed the old creation myth into a formula."*[3]

The interpretation of physics extends beyond painting and sculpture as well. Architecture as a medium presents a unique opportunity for artistic expression. It is a form of art that inherently draws upon the sequential experience of physical environments in a way that another medium might not. A building, while often thought of as a sort of three-dimensional object, has a temporal component; its occupants move through it and experience different parts of the building at different times and from different angles. There are numerous characteristics common to both architecture and physics, such as the geometry of space or the texture of matter. The necessity of movement and exploration to the experience of a building, combined with the tactility of the body moving through a physical space,

[3] Franz Marc, "Aphorism 35," in *Briefe, Aufzeichnungen Und Aphorismen* (Berlin: P. Cassirer, 1920), 1:128, quoted in Lynn Gamwell and Neil deGrasse Tyson, *Exploring the Invisible: Art, Science, and the Spiritual*, Revised and expanded edition (Princeton, New Jersey: Princeton University Press, 2020), 248.

renders architecture a unique intermediary through which to convey ideas about the physical world.

A number of architects, painters, and sculptors throughout history have expressed an enthusiasm towards incorporating concepts taken explicitly from discoveries in physics into their work. For instance, in 1772 Italian architect Nicola Carletti published his book *Instituzioni d'Architettura Civile* in which he expressed his enthusiasm for Newton's philosophy and his personal desire to apply it to architecture.[4]

However, there remains a comparative void of artistic work of any kind considering more modern advances in physics and what the discoveries or theories suggest about the nature of our universe. To explore the implications of more recent theories in modern physics towards hierarchical organization and the nature of matter, space, time, and motion, in this thesis I produce an architectural design project to bridge some of this gap.

1.3 THESIS ORGANIZATION

This thesis is divided into two main portions: historical context and design exploration.

1.3.1 HISTORICAL CONTEXT

The contextual, historical portion of the thesis is organized into the following chapters:

2. Pre-Scientific Revolution
3. The Scientific Revolution
4. Relativity
5. Quantum Mechanics
6. A Unified Theory of Physics

To investigate how recent advancements in science have affected cosmological views, I will need to examine how science has affected cosmology in the past to understand how art and architecture have been intertwined historically. I will focus on before and after the Scientific Revolution in Europe, roughly between the mid-1500s during the second half of the Renaissance and up until the late 1600s, as this is the part of scientific history that most directly leads into Western science today. Some historical figures, such as Johannes Kepler, will show up in both of the first

[4] Alberto Pérez-Gómez, *Architecture and the Crisis of Modern Science* (Cambridge, Massachusetts: MIT Press, 1983), 112.

two chapters, since their ideas came out of pre-Scientific Revolution ideas but later significantly influenced the Scientific Revolution.

After examining the scientific and historical context on both sides of the Scientific Revolution, I will examine how modern physics, particularly quantum mechanics, Einstein's theory of relativity, and the search for a unified theory of physics have affected our view of the universe.

Each of the chapters about historical context is split into two sections. I will first examine the history and details of the relevant physics concepts. I will then analyse the ideas' ramifications for the following characteristics of cosmology and architecture:

1. **Hierarchy and the Observer:** how the world is organized and the viewpoint from which we imagine it
2. **Force and Matter:** the physical world around us that we can feel and touch
3. **Space, Time, and Motion:** the shape of the world and how we move through it

Throughout my reading, I have found that these characteristics have changed the most according to scientifically driven changes in cosmological views and are also appropriate to frame an architectural discussion.

1.3.2 DESIGN EXPLORATION

In the final chapter I design a museum of physics to explore how to communicate with architecture what modern physics says about the universe, particularly considering the above characteristics.

2 PRE-SCIENTIFIC REVOLUTION

2.1 CONTEXT

Models of the universe, particularly before the Scientific Revolution, are incredibly diverse and vary wildly from culture to culture. I am choosing concepts that I was exposed to during my schooling in Canada, which followed a typical Western education in modern physics, and concepts that I see as being part of a reasonably direct lineage of ideas leading up to modern physics.

2.1.1 ANCIENT GREECE

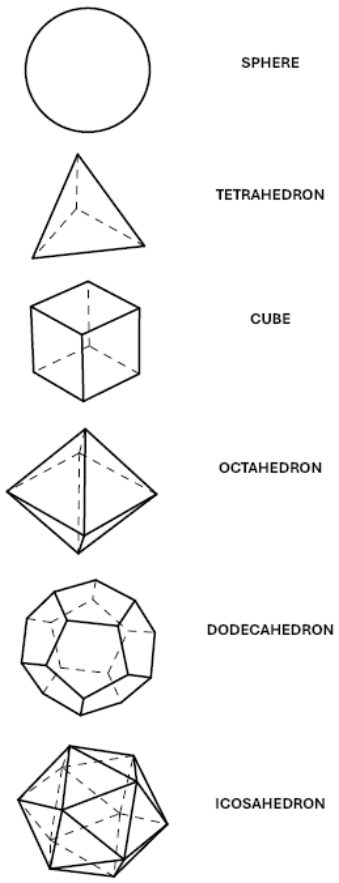
EUCLIDEAN GEOMETRY

Pure geometry is not something that exists naturally in the world; it is instead a way of *describing* the shape of objects or spaces. As such, mathematicians must clearly define a given version of geometry.

Euclid, a Greek mathematician who lived around the year 300 B.C.E., wrote a foundational text—surviving to today only in translations and adaptations—to the field of mathematics: *The Elements*. The book is a compilation of 465 mathematical theorems, many of which are about geometry. The theorems define geometrical concepts, such as points, lines, angles, and the relationships between them. Euclid's definitions are, because they are mathematical proofs, true under limited, well-defined conditions. His theorems apply primarily to geometry on flat planes.

The geometrical definitions Euclid uses to frame the contents of *The Elements* are simple enough to apply to the geometry of our everyday experience. For example, he describes parallel lines as being lines in the same plane that, when extended infinitely in either direction, will never meet; this is the behaviour of, say, the parallel sides of floor tiles or of the parallel pieces of orthogonal structural framing.

Figure 1
The sphere and the Platonic solids



THE PLATONIC SOLIDS

In mathematics before the Scientific Revolution, the five Platonic solids—tetrahedron, cube, octahedron, dodecahedron, and icosahedron (see **Figure 1**)— were of great importance. Each of these polyhedra are made up of a repeated single symmetrical, regular polygon. Additionally, the Platonic solids have geometrical relationships to each other: by connecting the midpoints of all the octahedron's faces, a cube is formed. The same can be done with the icosahedron for the dodecahedron, and the tetrahedron for itself.[5] These two features together make these shapes more ideal than other polyhedra. Spheres were also important, as they were also a perfect shape.

The Platonic solids are related to early conceptions of the material world in that each of them is associated with one of the four elements, or aether in the case of the dodecahedron. The generative relationships between the solids then imply relations between the elements. For instance, fire, which is denoted by the tetrahedron, can only "generate" fire and not the other elements.[6] The Platonic solids and their relationships to each other and the elements of matter form a model of how matter, shape, and form can be organized.

ATOMS AND MATTER

The shape of objects is not their only characteristic. Their material composition, too, has been a subject of debate over the centuries.

Ancient conceptions of matter were different than what we know today. Greek philosopher Anaximander, for example, thought that change occurred due to the interaction of opposites such as dryness and moistness or hot and cold.[7] This demonstrates an interest in the tension between variances in a single characteristic and the idea of, presumably, a point of stable equilibrium—or, in other words, a state in which things "should" be. I see this as playing into the idea that perfection requires an unchanging world.

At other times, early philosophers were remarkably prescient. Leucippus—another philosopher in Ancient Greece—suggested that there exists a lower limit to divisibility of space, time, and material: that the universe is granular

[5] Stephen Skinner, *Sacred Geometry: Deciphering the Code*, 1st pbk. ed (New York: Sterling, 2009), 54–55.
[6] Skinner, 54–55.
[7] José Luis Mateo and Florian Sauter, eds., *Earth - Water - Air - Fire: The Four Elements and Architecture* (New York, N.Y.: ACTAR, 2014), 10.

rather than continuous. His student Democritus called the hypothetical smallest possible piece of matter, matter that could no longer be divided, the **atom**, a name which we use for a similar concept today. Fellow Greek philosopher Aristotle disagreed with the suggestion that something that appeared continuous, including distance and time, could in reality be made up of indivisible parts.[8]

Democritus's idea of how atoms behave, however, diverges from what we now know: Democritus thought that atoms' only characteristic was their shape, and that things like temperature and colour were "opinion."[9] He thought that the way atoms arrange themselves is what produces characteristics, and which characteristics were produced was random. Others, such as Plato and Aristotle, disagreed with Democritus' interpretation of matter as they disliked the idea that anything in the universe could be purposeless. Plato, for example, uses his mentor Socrates as a mouthpiece for his criticisms of Democritus in his dialogue *Phaedro*. In it, Socrates expresses frustration at the suggestion the Earth is round without its being round for a purpose—he wants to know "how being at the centre was of benefit to the Earth."[10]

The Roman philosopher Lucretius promoted and added to Democritus's atomic ideas. In his poem *De rerum natura* he makes several assertions, such as that nothing can be created out of nothing, that all atoms are constantly in motion even though we cannot sense it, and that even sentience arises from the combination of insentient atoms.[11]

SPACE

Space in ancient conception was likewise different.

While Democritus suggested otherwise, space, before the late 1500s, was "a property of bodies and not the receptacle in which bodies exist."[12] Truly empty space, after all, is not part of the average daily human experience, even now: visible gaps between objects are filled by air, not a

8 Marion Smoothey, *Ratio and Proportion* (New York: Marshall Cavendish, 1995), 123.

9 Carlo Rovelli, *Reality Is Not What It Seems: The Journey to Quantum Gravity*, trans. Simon Carnell and Erica Segre, First Riverhead trade paperback edition (New York: Riverhead Books, 2018).

10 Plato, *Phaedro*, ed. David Gallop (Oxford, UK: Oxford University Press, 2009), quoted in Rovelli, 23.

11 Alan L. Mackay, "Lucretius: Atoms and Opinions," *Interdisciplinary Science Reviews* 16, no. 2 (1991): 127.

12 Clara Germana Gonçalves, "Architecture and Modern Science: The Mathematics of the Circle—Arithmetic and Geometry as Figure and Symbol in the Renaissance and Baroque," in *Modernity, Frontiers and Revolutions*, ed. Maria Do Rosário Monteiro, Mário S. Ming Kong, and Maria João Pereira Neto, 1st ed. (CRC Press, 2018), 43, https://doi.org/10.1201/9780429399831-6.

vacuum. While Democritus believed that space is an entity distinct from matter, Aristotle argued that the idea of genuine nothingness between two objects is absurd because for there to be space between the objects, then there must be *something*. [13]

2.1.2 THE PTOLEMAIC MODEL

The ideas about geometry and space as discussed above were used in the construction of the ancient model of the universe.

Earth was stationary, at the centre of a spherical universe. Around it were eight concentric spheres, one for each of the "planets", which then included the Sun and the Moon, and another for the stars. Beyond these lay the heavenly realm. Below the planetary spheres were other layers, one layer for each of the so-called four elements.

The universe as a whole was, because it was created by divine forces, fixed. The spheres moved by a sort of clockwork: the outermost sphere moved the next sphere, which moved the next sphere, and so on. The more divine a sphere was, the more unchanging and further from the centre it was. All temporary phenomena that were observed in the sky, such as comets and meteors, were assumed to happen underneath the first sphere, under the Moon and close to the Earth.

The orbits of the seven planets on their respective spheres were perfect shapes—circles—despite the fact that calculations performed using circular orbits would inevitably become out of sync with observations. These discrepancies were, in fact, "fixed" with the additional of yet more perfect circular orbits – "epicycles" – whose centres would travel along the larger circular orbits and produce effects such as Mars' retrograde motion.

2.1.3 INFINITY

The universe was thought to be finite before the Scientific Revolution, but there were those who discussed the potential infinity of the cosmos, particularly as it related to interpretation of God's infinity in Christianity. Nicholas of Cusa, a German Catholic Cardinal during the end of the Middle Ages, asserted that the universe was infinite.[14] On the other hand, Christina, queen of Sweden in the 1600s, doubted that an infinite universe would allow humanity

[13] Rovelli, *Reality Is Not What It Seems*.
[14] Koyré, *From the Closed World to the Infinite Universe*, 6.

to continue to occupy the place of central importance given to it in Christian thought.

However, there was also a distinction between what Nicholas of Cusa describes as infinite in the sense of without bounds, and infinite in the sense that God is infinite. For Nicholas of Cusa, the natural universe itself was a contracted image of God, God being "a sphere of which the centre is everywhere, and the circumference nowhere."[15] He also discusses the imprecisions that are observable in our universe, such as there being no stars perfectly aligned with the poles—only nearly aligned—and that the so-called eight spheres' axes precess[16] and are not fixed.

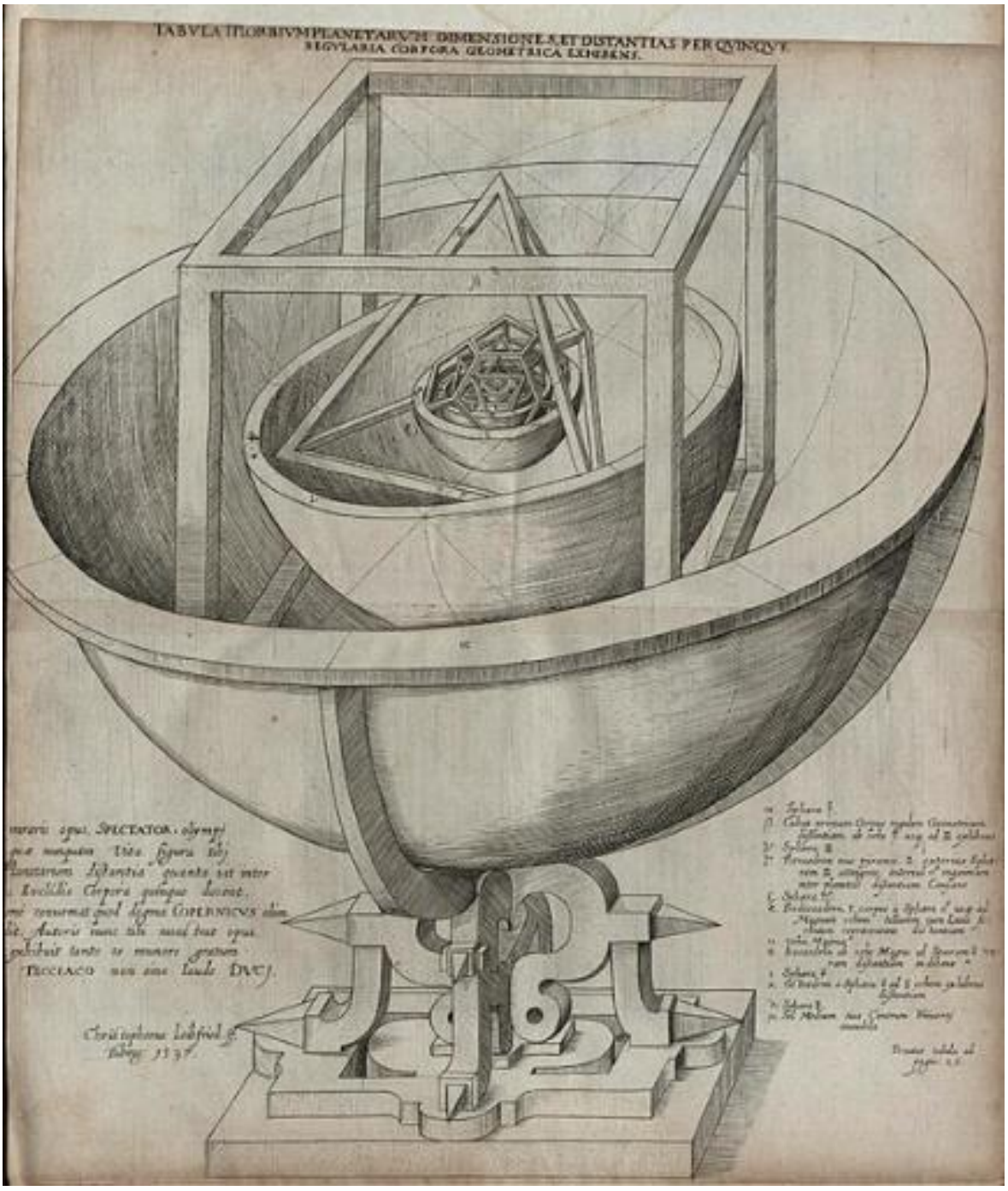
Cusa also observes that motion cannot be observed except by comparison to something else—a principle fundamental to Albert Einstein's later theory of relativity. Cusa acknowledges that the positions of celestial bodies, including Earth, are not fixed, because there can be no true centre in an infinite universe.[17] It is important to note that while Nicholas of Cusa came up with the basic principle of relativity centuries before Einstein, it did not catch on. He does not base his thinking on astronomical science, which was limited. In fact, he even believed that the moon and Earth give off their own light. It was not until later, when these ideas were backed more scientifically, that they became popular.

2.1.4 KEPLER'S EARLY MODEL

The Ptolemaic model of the universe remained dominant up until around the 17th century. The 17th-century German astronomer Johannes Kepler, before making later contributions to physics that became fundamental to modern astronomy, created a model of the universe that he described in his book *Mysterium Cosmographicum*, published in 1596. I will discuss Kepler again in **Chapter 3** in the context of his contributions to the heliocentric model of the universe, but he occupies a point in history where heliocentrism was still being developed, so some of his ideas are relevant here.

[15] Gonçalves, "Architecture and Modern Science," 46.
[16] Precession refers to the gradual shifting of a spinning object's axis around another axis.
[17] Koyré, *From the Closed World to the Infinite Universe*, 12–13.

Figure 2
Kepler's early model of the universe that uses the Platonic solids to construct the distances between planetary orbits



At this point in time, Kepler was already aware of and supported the idea of a heliocentric model of the universe put forth earlier by Polish astronomer Nicolaus Copernicus. Kepler's early model (see **Figure 2**) was, therefore, heliocentric rather than geocentric as the Ptolemaic model is, but Kepler still retained an attachment to earlier hierarchical ideas about the importance of perfect shapes.

Kepler's early model put the Sun at the centre of the universe with the planets orbiting around it, and then described the distances between each concentric planetary sphere using both Pythagoras's musical intervals from the 6th century B.C.E. and the Platonic solids.[18] He placed the orbits of the planets each on one of the Platonic solids, which then enveloped the next Platonic solid. Circles inscribed[19] in each of the solids described the location of the spheres, which agreed with observations remarkably accurately.

Kepler was theologically driven to describe the orbits of the planets using the perfect Platonic solids. He believed that the structure of the universe reflected God himself and sought to incorporate the evidence pointing towards heliocentrism into a heliocentric model of the universe that was nonetheless hierarchically perfect, with its geometrical proportions dictated by a higher power.[20]

2.2 HIERARCHY AND THE OBSERVER

Taken together, these moments in physics show a distinctly fixed hierarchy in the world, one that is dictated by a higher power and imposed upon the lower and imperfect. We can examine how this hierarchy appears within architecture.

IDEAL GEOMETRY

The celestial spheres in the Ptolemaic model acting like clockwork from the outside in is a hierarchy imposed from the top down. The insistence on the use of circles to correct observed deviations in planetary paths reflected the idea that the heavens created by God were perfect and everlasting. As stated earlier, Plato did not like the idea

[18] Skinner, *Sacred Geometry*, 79.

[19] In geometry, a shape is said to be *inscribed* within another shape when it fits inside the larger shape as closely as possible.

[20] Peter Barker and Bernard R. Goldstein, "Theological Foundations of Kepler's Astronomy," *Osiris* 16 (January 2001): 88–113, https://doi.org/10.1086/649340.

Figure 3
Engraving of Bramante's Tempietto (1570) by Andrea Palladio. The dome in section is half of a circle.

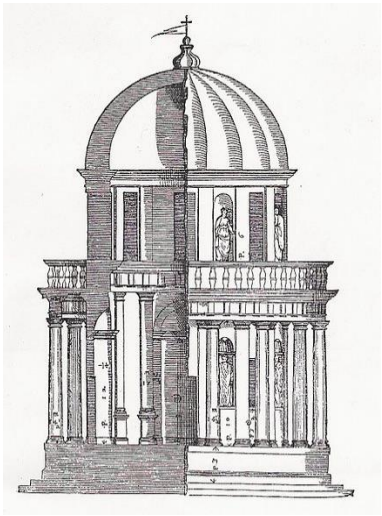
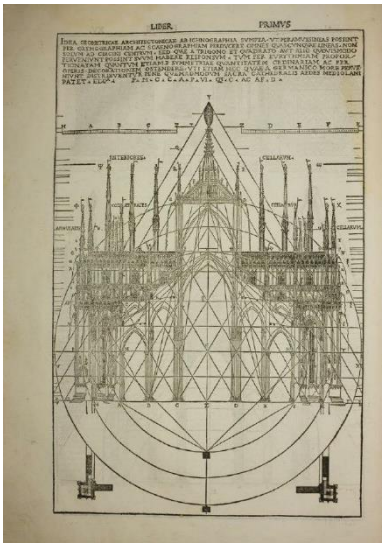


Figure 4
The front elevation of Milan Cathedral, as drawn by Cesare Cesariano (1521). The guidelines show how a series of concentric circles was used to arrange architectural elements.



that the Earth was round because he could not see how the Earth being round served a purpose; this shows that his cosmological view relied on there being some higher power to create and organize the world.

Kepler's later model of the universe based on the Platonic solids had no scientific justification; that the distances of the planets happened to match quite closely with the ratios of the Platonic solids was pure coincidence. Instead, he constructed it the way he did because he thought the universe ought to be perfect. The structure of the universe he created was idealized and imposed a top-down hierarchy based on what the universe "should" be rather than what existed. Kepler imposed the Platonic solids on the structure of the cosmos, and they happened to fit.

The fascination with the Platonic solids shows itself again in architecture, even up to and past the Renaissance. The shapes show up slightly indirectly – the more complex Platonic solids would make for impractical buildings – in the use of symmetry, the ratios that Kepler used in his initial model of the universe,[21] and in the use of regular *polygons*, the two-dimensional equivalents of the Platonic solids.

Circles, particularly, were used as a reflection of Plato's cosmology in architecture.[22] Andrea Palladio—an Italian architect during the 1500s—describes circles as being appropriate for churches because they demonstrate "extremely well the unity, the infinite essence, the uniformity and the justice of God."[23] He held up the Tempietto—a tomb in Rome designed by Bramante—as a prime example of the use of the circle to evoke God's perfection (see **Figure 3**).[24]

Another architectural example of the use of geometry that reflects the structure of the universe Cesare Cesariano's analysis of Milan Cathedral. In his 1521 translation of Roman architect Vitruvius' *Ten Books on Architecture*, he analyses the shapes used in the design of the cathedral.[25] The front elevation of the cathedral is based on a series of seven concentric circles, with elements on the façade lining up with points on each circle (see **Figure 4**).[26] The

21 Smoothey, *Ratio and Proportion*, 133.
22 Rudolf Wittkower, *Architectural Principles in the Age of Humanism* (London New York: Academy Editions St. Martin's Press, 1988), 32.
23 Andrea Palladio, *Fourth Book on Temples*, The Four Books of Architecture, 1560, quoted in Wittkower, 32.
24 Wittkower, 33–34.
25 Small, "Circling Round Vitruvius, Linear Perspective, and the Design of Roman Wall Painting," *Arts* 8, no. 3 (September 14, 2019): 12, https://doi.org/10.3390/arts8030118.
26 Skinner, *Sacred Geometry*, 132–33.

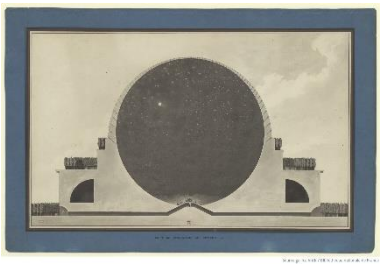
centre of the circles is a third of the way up from the ground to the level of the flat portion of the roof. Equilateral triangles on Cesariano's original drawing of the front façade lay on the ground and tangent with the circles. The drawing also shows a partial square and a partial hexagon inscribed within one of the circles.

I assert that the use of the Platonic shapes in architecture is an instance of a hierarchy imposed from a higher power. The buildings are organized to match idealized shapes by using the Platonic shapes as their basis for organization and using concentric repetition around central points. Vitruvius even recommended that buildings be proportioned so as to "correct" the distortion of their dimensions that occurs due to perspective.[27] This forced correction of the perceived geometry demonstrates an unusual interplay between the desire to construct buildings that *appeared* to be perfect and the actual geometrical reality of the building. This tension carries, to me, an implication that perception is the true location of reality—*ideal* reality—while the imperfect physical world is simply the lens through which we can observe that ideal reality. While I do not mean to suggest that this interpretation was Vitruvius's intent, the distortion of geometry to create the perception of perfect geometry evokes the Platonic concept of "form" as the true essence of a thing, while matter and objects in the physical world only approximate that essence.

It is not only Platonic shapes that can be seen as a form of hierarchical organization. The use of scale and the idea of infinity, too, can be examined as hierarchical thinking. Nicholas of Cusa's suggestion that the world was infinite was primarily because of his ideas about the nature of God, rather than based on physical evidence.

Étienne-Louis Boullée's Cenotaph for Isaac Newton (see **Figure 5**) is an interesting architectural case of the use of both spheres and scale. We can tell by its name alone that Boullée designed it after Newton; in fact, it was drawn over fifty years after Newton's death in 1727. This was after the Scientific Revolution. However, despite the Cenotaph's namesake, its actual design is much more reflective of the pre-Enlightenment conception of the cosmos that it is of contemporary astronomical knowledge, and so I include it here. The Cenotaph for Isaac Newton is an enormous spherical shell, hollowed out and with an entry tunnel rising up from beneath that brings visitors to a platform. The

Figure 5
Section view of Étienne-Louis Boullée's *Cenotaph for Isaac Newton* (1784) during the day. The spherical dome of the building can be seen clearly in section.



[27] Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 32.

shell is punctured to create star-like lights that are evocative of the fixed sphere of the stars in the cosmology of before the Scientific Revolution.

The Cenotaph's spherical shape implies a perfection of the universe that, at the time Boullée designed it, was known to not exist. Still, the desire for perfection remains. Architectural historian Alberto Pérez-Gómez, in his book *Architecture and the Crisis of Modern Science,* describes the Cenotaph as a "forceful image of a hierarchical and still undivided cosmos."[28] The effect of the huge scale of the building's shell is to give a sense of being small and insignificant, even when you are standing at the centre.

2.3 FORCE AND MATTER

The perceived behaviour of force and matter before the Scientific Revolution was related to the previously discussed ideas about hierarchical organization. The analysis within this section—as well as the next—are therefore limited. The rigidity of the universe's structure, it seems to me, held the other characteristics in check. Force and matter, as well as space, time, and motion, were dominated by the hierarchical view of the cosmos.

As discussed in **Section 2.1.2**, the outer spheres of the Ptolemaic model drove the motions of the interior spheres. Both force and matter, then, were strongly tied to their location within the hierarchy of the universe. Characteristics and behaviour were not universal, and instead applied to only portions of the universe.

The early conception of the cosmos as a series of concentric spheres making up a "hierarchically ordered whole"[29] set up a system where value in the hierarchy determined location and characteristics of matter: dark, heavy, and imperfect matter existing within the lowest sphere, and higher and lighter matter existed within the upper heavenly spheres.

Additionally, matter of any kind was seen as the imperfect manifestation of ideal geometrical forms. Some ancient Greek philosophers separated the world we see from the "geometrical space of the stars and planets, which was conceived as a truly ideal entity."[30]

[28] Pérez-Gómez, 139.
[29] Koyré, *From the Closed World to the Infinite Universe*, 4.
[30] Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 40.

2.4 SPACE, TIME, AND MOTION

Motion and change over time, we can see, was not valued: moving objects were placed in the lowest, least divine spheres because their imperfect, non-circular, and temporary paths meant that they were not divine.

Aristotle implies that motions, like the structure of the universe, are preordained. He says that everything in nature has a "characteristic source of motion stored within it" and that the four elements that the physical world is made up of each have a built-in tendency of motion, with fire moving upwards and earth moving downwards.[31]

The fact that motion exists raised questions about the nature of space for Aristotle. He says in his writing that the existence of movement and change implies that space is different from matter, and also that it could fit with the idea that there exists void. Aristotle argues, however, that true void cannot exist, since it would render movement impossible.[32]

Aristotle also describes the *directions* that are possible for motion as being in relation to "the centre" of the universe; moving "upwards" to Aristotle meant moving away from the centre, rather than, say, moving in the direction of a line drawn from the feet to the head when standing.[33] Other philosophers, such as Epicurus, described directions as if imagining a set of background coordinate axes.[34] However, Epicurus thought that atoms would inherently move "downwards" through space; his version of the directions of space meant that "down" was the same for *all* atoms. This raised the issue of how change would ever occur, as atoms would never encounter each other.[35]

[31] Smoothey, *Ratio and Proportion*, 121.
[32] Smoothey, 123.
[33] David Marshall Miller, *Representing Space in the Scientific Revolution*, 1st ed. (Cambridge University Press, 2014), 12–13, https://doi.org/10.1017/CBO9781107110656.
[34] Miller, 14.
[35] Miller, 15.

3 THE SCIENTIFIC REVOLUTION

3.1 CONTEXT

During the mid-1500s to the late 1600s, there was a remarkable series of discoveries that informed the initial development of what we now call science. These discoveries covered a wide range of fields—math, biology, chemistry—and included crucial developments in physics and astronomy.

The discoveries that are relevant to this thesis centre around moving from a geocentric universe to a heliocentric universe.

3.1.1 THE PLACE OF THE SUN

The Polish astronomer Nicolaus Copernicus published his book *On the Revolutions of the Celestial Spheres* in 1543. It detailed Copernicus's heliocentric model of the universe, which agreed more closely with the observed motions of the planets than did the geocentric model. His model was particularly successful in predicting the retrograde motion of planets, the same problem that had previously been "solved" using epicycles.

Copernicus kept the pre-existing distant fixed sphere of the stars in his heliocentric model of the universe. The planets still travelled on circular orbits. He did, however, also posit that rather than there being different layers of the cosmos made of different substances and adhering to different laws, that the entirety of the universe followed the same fundamental laws and was made of the same components.[36] Copernicus valued the "symmetric harmony of the universe"[37] and this flowed into his version of the universe in that he considered the Earth and celestial bodies to be made of the same material.

3.1.2 THE TELESCOPE

Later astronomers would have access to better data due to technological advancements. Danish astronomer Tycho

[36] Koyré, *From the Closed World to the Infinite Universe*.
[37] Gonçalves, "Architecture and Modern Science," 45.

Brahe used custom-made instruments to make measurements more accurate than previously possible. Despite the remaining limitations of his instruments, he was unable to measure any stellar parallax.[38] This proved that the stars were incredibly distant.

Kepler, who was Tycho's student, used records of Tycho's improved observations to develop more accurate mathematical laws of planetary motion. The model he used to fit his equations to the data placed the Sun at one of the two foci of elliptical, rather than circular, orbits. This model's predictions were more accurate than the model using circular orbits and epicycles had been able to produce, and also simpler to calculate.

In the early 1600s, the telescope was invented; this provided the Italian astronomer Galileo Galilei a tool to observe the sky more closely than had been previously possible. He made a number of discoveries that would help to solidify the heliocentric model of the universe. By around the year 1700, the geocentric model had fallen out of favour entirely.

STARS

With the telescope, Galileo was able to measure the angular size of celestial objects much more accurately than astronomers relying on naked eye observations had been able to. He found, unsurprisingly, that the angular size of objects like the Moon and the Sun increased greatly when viewed through a telescope. However, he found unexpectedly that the angular size of stars did *not* change; this implied that the stars were even more distant than previously assumed.

THE SUN

Galileo was able to track the motion of sunspots on the Sun's surface, which were previously unobservable. The spots' motion implied that the Sun rotated, which brought forth the possibility—as Galileo himself argued—that the Earth also rotated.

THE MOON

Prior to the invention of the telescope, people believed that celestial objects were perfectly spherical; this made sense, given that the sphere was a perfect shape, and the further from Earth and the closer to heaven you went, the more perfect the shapes ought to be.

[38] Parallax is the apparent change in position of an object when viewed from a different angle. Stellar parallax—the parallax of stars—is incredibly small due to stars' distance from us.

However, the telescope unveiled the details of the Moon's surface, which was pitted with craters and shadowed with mountains and valleys, similarly to the Earth's imperfect surface. This knowledge raised the possibility that Earth, too, was a celestial object.

MOONS OF JUPITER

Galileo also used the telescope to observe the planet Jupiter. He found that Jupiter, instead of existing alone, was accompanied by several smaller objects. These objects, when observed over multiple nights, changed position. Galileo charted their movements and found that they could be explained easily by imagining them to be orbiting Jupiter, in the same way that the Moon orbits the Earth.

If something other than Earth had satellites, then perhaps it was possible that anything could have them. The discovery of Jupiter's moons destabilized the idea that everything had to revolve around the Earth, and opened up the idea that the Earth could itself be a satellite rather than the centre of everything.

PHASES OF VENUS

The most direct and incontrovertible piece of evidence Galileo found in favour of a Sun-centred model of the world, was his observations of the phases of Venus.

Like the Moon, Venus experiences phases as the angle between the Earth, the Sun, and Venus itself shifts as time passes. Unlike the Moon, however, we do not see a "full" range of the phases of Venus: Galileo, when charting its appearance, could mostly only observe its dark, unilluminated side, with sometimes a sliver of illuminated crescent. This told him that Venus was typically between the Earth and the Sun, unless it was somehow completely out of our view—and it would be completely out of our view if it were behind the Sun. Galileo realized that this meant that Venus must revolve around the Sun, not around Earth. His measurements of the angular size of Venus, which was larger when it was fully in shadow than when it was partially lit, confirmed that Venus moved towards and away from us as it orbited the Sun.

3.1.3 INERTIAL MOTION

Observations of celestial phenomena were not the only factors in the establishment of the heliocentric universe. Experiments on Earth, too, proved necessary for explaining the motion of the planets.

Galileo conducted an experiment where he rolled balls down a slope and observed their speeds. He found that regardless of the balls' weights, they fell at the same speed, and that the speed increased proportionally to how long they'd been moving. Prior to this, it was believed that objects fell at speeds proportional to their weights. Galileo's experiments led him to conclude that motion is the natural state of things, and that it is the *cessation* of motion that requires input.

French philosopher and scientist René Descartes expanded on Galileo's discovery and pointed out that objects in motion will continue to move in a straight, and not a curved, line.[39] This raised questions about motion within both the geocentric *and* the heliocentric models of the universe, which both required orbiting motions. A force of some kind was required to account for this, and to account for the curving motion of objects falling to the ground. Explaining this force was part of what led to the discovery of gravity.

3.1.4 GRAVITY

In the mid-1600s, Robert Hooke has used a demonstration with a wire connected to a weight to show that a force acting towards the centre could explain orbital motion.

English physicist and mathematician Sir Isaac Newton synthesized Galileo's and Hooke's ideas about motion into his laws of motion:

1. An object travelling at a constant velocity will remain travelling at that constant velocity unless it is acted upon by an outside force. An object at rest will remain at rest unless it is acted upon by an outside force.
2. A force is proportional to the mass of an object and the acceleration the force produces on that object.
3. A force produced by one object on another will result in an equal and opposite force produced by the second object on the first.

Newton applied these laws of motion to the concept of gravity. He found two things. Firstly, he determined that the centripetal force required to keep a planet in orbit is proportional to its distance from the Sun. Secondly, he asked what would happen if you shot an object out of a cannon at high speed from a high elevation—if the arc the object followed was sufficiently wide, would it go into

[39] John D. Fix, *Astronomy: Journey to the Cosmic Frontier*, 4th ed (New York, NY: McGraw-Hill Higher Education, 2006), 81.

orbit around the Earth? In asking this question, Newton discovered that the same force that pulled objects to the ground was the same force that kept the planets in motion.

3.1.5 THE EXPANSION OF LIGHT

In addition to his work on gravity, Newton also made discoveries regarding the behaviour of light. When using a lens to form images of the sky, he noticed that the light at the edge of the images was coloured. He blocked out the light from his window, except for a single beam of light, in the path of which he then placed a glass prism. The prism revealed the hidden nature of plain white light: it split the light apart into its constituent colours.[40]

3.2 HIERARCHY AND THE OBSERVER

FLATTENING THE HIERARCHY

These discoveries together added up to a flattening of the established hierarchy of the cosmos. The Earth now orbited the Sun and was therefore not the centre of everything. Copernicus' suggestion that the universe followed the same fundamental laws and was all made of the same materials, as well as Newton's discovery that the same force acts to keep the planets in motion and to make ordinary objects fall to the ground, made the distant heavens behave more like what we experience on Earth.

Giordano Bruno, an Italian philosopher in the second half of the 1500s, after Copernicus, imagined that just as we on Earth call the Earth the centre of the universe, that people living on the Moon would call the Moon the centre of the universe.[41] We can see here a shifting in thought about how the universe is structured, and a decentering of Earth. This does not necessarily imply that Earth was therefore less *important*, as one might assume—the farther from the centre of the pre-Copernican universe, the more divine a sphere and its contents were. And the only thing more central than the Earth, in that model, was Hell itself. Opposition to Copernicus's heliocentric worldview was partly that Earth's removal from the centre gave it, and

[40] Paul G. Hewitt, "Focus on Physics: Newton's Prisms," *The Science Teacher* 88, no. 2 (December 2020): 16–17.

[41] Koyré, *From the Closed World to the Infinite Universe*.

humanity, a place of too *much* honour, putting it too close to the divine.[42]

However, this interpretation still serves to illustrate that the distance between Earth and the heavens in the hierarchy was shrinking. Hierarchies were not done away with altogether, but instead adjusted; cosmological change is a slow process. God was not removed from cosmology altogether, but instead moved from a distant untouchable sphere of existence to a "force that endorsed the perpetual miracle of everyday life."[43] While the divine was still important, its place was moved closer to us within the hierarchy.

Like the pre-Copernican worldview, Copernicus' cosmology maintains that the universe retains a hierarchy, albeit one that is less rigid, in that it kept the fixed sphere of the stars. Copernican cosmology, then, maintains that the universe is well-ordered and finite.[44]

Figure 6
Triumph of St. Ignatius of Loyola. Photo: Livio Andronico. License: CC BY-SA 4.0. This photo is taken from the point on the floor at which the perspective of the fresco appears correctly.



THE REVELATION OF THE HIDDEN

The move to a heliocentric model of the universe moved the divine closer, and Newton's prism experiments brought previously unknown knowledge about the hidden mechanisms of nature closer. This suggested a limit to our abilities as the observer, and that there might be a different perspective *below* what we observe, and not only a hidden perspective of a higher being imposed on us from above. Hidden physical features of the world that cannot be observed without instruments are an early part of the questioning of the accuracy of what we observe at the surface and of the existence of a single, observable truth.

Art in the seventeenth century shows an interest in playing with hidden perspective and meaning. Anamorphosis—a type of perspective projection that could be used to distort an image to hide it within a painting—became popular during the first half of the seventeenth century. This is in contrast to the earlier use of distorted elements in architecture to *correct* distorted perspective; as described by Pérez-Gómez, "the primacy of undistorted presence was replaced by the primacy of distorted appearance." I see this as an increasing interest in the human perception's effect on the perception of reality and the idea that point of view can change observed reality.

[42] Smoothey, *Ratio and Proportion*, 254.
[43] Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 82.
[44] Koyré, *From the Closed World to the Infinite Universe*.

The seventeenth-century Italian artist Andrea Pozzo, for example, laid out his frescoes on the ceilings of churches in such a way that their perspective worked from only one predetermined point (see **Figure 6**), which would be marked on the churches' floors. This use of perspective "revealed a true hierarchical and transcendental vision that appeared only when man occupied his place in the geometrical structure of the Creation."[45] I consider this to be a play on the role of the observer. It explicitly makes human observation a necessary act in the presence of the divine; I would argue that this is an example of the reduction of the hierarchy between humanity and the divine, despite the place of honour still given to the divine.

S. Carlo alle Quattro Fontane (see **Figure 7**), designed by Italian architect Francesco Borromini in the 1600s, exhibits a marked difference in style between its upper and lower storeys. The lower storeys appear chaotic like nature, and the upper storeys are more ordered like the ideal divine. However, the supposedly chaotic lower storeys still follow a set of geometrical rules, which reflects "the inherent skeleton of the universe as a whole."[46] The divine order above rules the chaos of nature below. This contrast between the two styles of geometry do not appear in other contemporary churches, and that instead other contemporary churches use more obviously clear geometrical rules.[47]

Figure 7
S. Carlo alle Quattro Fontane façade. Photo by Architas. License: CC BY-SA 4.0. The style of the upper and lower storeys differs, with the lower storey representing nature and the upper storey representing the divine.



MATHEMATIZATION

In contrast to experiments with immediately apparent physical results like Newton's prisms, other scientific work, like Kepler's laws of planetary motion, required the use of mathematical modelling. Mathematics was an area of scientific focus during the Renaissance, and advances in the field brought about changes in ideas about the use of geometry. Mathematics became used as a more widespread method of understanding the world; it was thought of as a language that could be used to understand divine intentions behind the design of the world.[48]

In fact, Galileo argued that everything in nature was mathematical.[49] His discoveries about the structure of the universe were based in observable evidence and, importantly, their mathematical underpinnings, rather than previous versions of cosmology whose "transcendental conclu-

45 Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 178.
46 *Architecture and Mathematics from Antiquity to the Future: The 1500s to the Future*, vol. 2 (New York, NY: Springer Berlin Heidelberg, 2015), 223.
47 *Architecture and Mathematics from Antiquity to the Future*, 2:223.
48 Gonçalves, "Architecture and Modern Science," 44.
49 Gonçalves, 44.

sions existed beforehand."[50] Bruno likewise asserts that perception through the physical sense can be mistaken, and that the intellect is more reliable as a tool of scientific and philosophical knowledge.[51] Human perception therefore became decentred. The focus had begun to shift from direct perception to conceptual models. The agency of a human observer was becoming more necessary to the model of the universe, because now we had hidden truths of nature, like the spectrum of light, that required investigation to understand.[52]

Around the end of the seventeenth century, religion and scientific thought became more separate, and scientific thought became perceived as the more legitimate way to interpret reality. Before, the idea had been that the divine could be revealed through the material world; now, the material world was a "mere collection of inanimate objects."[53]

Discoveries in physics, and the use of mathematics to make those discoveries, supplanted the existing view of the cosmos and replaced it with a cosmos that ought to be explained with the smallest number of underlying rules.[54] The new view of the universe filtered into art and aesthetics; architectural language became a "theoretical problem" driven by the desire to find a set of rational laws for aesthetic styles.[55] The tools of science were becoming the tools of art, or, in other words, science influences worldview which can influence art and architecture.

The mathematization of the universe continued in the centuries following the Scientific Revolution. Geometry and mathematics became desirable for their ability to model and predict physical, observable phenomena, rather than for their symbolic meaning.[56]

I interpret the effect of this new energy of mathematical modelling as part of a shift of the role of the observer being filled by direct human experience to the true "observer" being the underlying physical laws of the universe.

[50] Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 18.
[51] Koyré, *From the Closed World to the Infinite Universe*, 45.
[52] Gonçalves, "Architecture and Modern Science," 44.
[53] Pérez-Gómez, *Architecture and the Crisis of Modern Science*, 11.
[54] Pérez-Gómez, 77.
[55] Pérez-Gómez, 11–12.
[56] Pérez-Gómez, 103–4.

3.3 FORCE AND MATTER

GRAVITY AND DISTORTION

The changing behaviour of the cosmos meant that architecture, too, changed. Newton's discovery of universal gravity particularly affected how shapes were used within buildings. Gravity and Newton's laws of motion meant that matter was more explicitly affected by forces; this new model of the universe contrasts with the Platonic idea of matter representing conceptual forms that reflect an ideal world of geometrical shapes.

Accordingly, unlike in the earlier Renaissance, architecture in the Baroque often contained complex geometries rather than platonic shapes such as ovals, ellipses, parabolas, and hyperbolas.[57] Architecture maintained the use of the "circle" but portrayed it in a distorted, elongated form, as if being pulled and warped by some external force. The world was no longer governed by the perfection of Platonic shapes.[58]

We can also see the circle distorted into an oval in the plan of St. Peter's Colonnade, designed by Bernini in the second half of the 1600s. The colonnade must distort in order to bend around, fanlike, to frame an elliptical piazza, creating variations in the distance between the columns (see **Figure 8**).[59]

Figure 8
St. Peter's Colonnade stretches perpendicularly from its main axis to create an elliptical, rather than circular, plaza. Photo by David Iliff. License: CC BY-SA 3.0.



Anamorphosis, too, can be thought of as an expression of the distortion of shapes by an applied force. A fresco created using anamorphic projection is distorted from all but a single point of view. From other viewpoints, the fresco appears stretched out as if pulled by some outside force.

3.4 SPACE, TIME, AND MOTION

THE INVENTION OF SPACE

The way people thought about space also changed. Before the Scientific Revolution, space was a characteristic of matter and not a property of the cosmos in its own right.[60] During and after the Scientific Revolution, space was primarily imagined instead as a void. The Italian philosopher Tommaso Campanella, around the turn of the seventeenth

[57] George L. Hersey, *Architecture and Geometry in the Age of the Baroque* (Chicago: University of Chicago Press, 2000).
[58] Gonçalves, "Architecture and Modern Science."
[59] Hersey, *Architecture and Geometry in the Age of the Baroque*.
[60] Gonçalves, "Architecture and Modern Science," 43.

century, for instance, described space as a receptacle that could hold corporeal material.[61] In the late sixteenth century, English physicist William Gilbert described space as a void that was made of nothing and produced no effects.[62]

We also see changes in the method of mapping out space. Before the Scientific Revolution, space had been thought of as centrally organized, spherically shaped, and emanating out from a point as in Aristotle's definitions of directions. After, it became instead predominantly thought of as *rectilinear*, according to an imaginary grid against which objects could move.[63] Rather than space being organized from a single privileged central point, space was organized with respect to a set of orthogonal axes. Directions—up, down, left, right, above, below, and so on—therefore became tied to an orientation in space, rather than being an inherent property of space.[64]

REST VERSUS MOTION

Space itself was not in motion—the universe outside of the Earth, Sun, and planets was still thought to be motionless. Newton assumed when describing his laws of motion that space itself is at rest.[65] Copernicus asserted that being at rest was "nobler and more divine than that of change and inconsistency" [66] and so it fit that the Earth that moved and not the rest of the universe.

However, the objects contained within this new void were, unlike everything beyond the lowest spheres in the Ptolemaic model, allowed to move. Architecture gained a greater sense of motion. While in the Renaissance, façades were sharp and geometrical, with vertical and horizontal lines intersecting, architecture in the Baroque used rounded, curving lines. Excessive ornamentation created a sense of movement around otherwise static architectural masses.[67] For example, the interior of S. Carlo alle Quattro Fontane uses a series of bays and niches of varying depths that are cut into the walls at different heights, to produce a rising sensation (see **Figure 9**).[68]

[61] Gonçalves, 43.
[62] Gonçalves, 43.
[63] Miller, *Representing Space in the Scientific Revolution*, 2.
[64] Miller, 7.
[65] Gamwell and Tyson, *Exploring the Invisible*.
[66] Koyré, *From the Closed World to the Infinite Universe*, 30.
[67] William Fleming, "The Element of Motion in Baroque Art and Music," 2023.
[68] *Architecture and Mathematics from Antiquity to the Future*.

Figure 9
S. Carlo alle Quattro Fontane interior. Photo by Oursana. License: CC0 1.0. The bays and niches cut into the walls rise up towards the main niche.



4 RELATIVITY

4.1 CONTEXT

The discovery in modern physics that has arguably had the largest effect on how we envision the shape of the universe is Einstein's theory of relativity. The theory lays out the mechanisms by which gravity, space, time, and motion all behave in unexpected and strange ways far different than what we are able to directly perceive. We can use the theory of relativity to frame the question of what the mutation of space and time could mean for our day-to-day perception of our physical experience.

There are two parts to Einstein's theory of relativity: **special relativity** and **general relativity**. Special relativity arises from the postulate that the laws of physics are the same in all inertial frames of reference.[69] We can think of special relativity as mostly relevant when travelling at speeds at appreciable fractions of the speed of light. General relativity, which was developed slightly later, deals with the behaviour of space and time in the presence of mass; these effects are most apparent when looking at truly immense amounts of mass, like stars and black holes.

4.1.1 THE LUMINIFEROUS AETHER

Before Einstein developed his theory of relativity, it was thought that light—which was known then to behave as a wave—needed a medium to propagate through, just as ocean waves propagate through water or sound waves propagate through air. This hypothetical substance was known as the **luminiferous aether**, which was suggested to be an intangible, jelly-like substance.

If we assume that light adheres to the principles of classical relativity,[70] then the speed of light should be dependent on an observer's speed relative to a wave of light. We

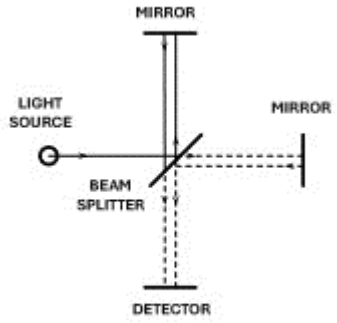
[69] An inertial frame of reference is a point of view that acts as a base from which the relative motion of objects can be measured, with time considered as a component. To avoid repetition, I will leave "inertial" as implied whenever I refer to frames of reference within this thesis.

[70] Classical relativity is intuitive. It is the idea that the motion of an object is relative to an observer's motion. For example, imagine you are standing next to a river, while your friend is standing in a boat moving down the river at some speed. To you, you are stationary and your friend is moving at the speed of the boat. To your friend, *they* are stationary and *you* are moving away.

would expect for light to be faster if we are moving towards its source—like how two cars moving towards each other have a higher speed relative to each other than to the stationary ground—and slower if we are moving away from its source.

However, bizarrely, when testing the speed of light, it was found to be constant in all directions and speeds, in direct contradiction to classical relativity. Albert A. Michelson was the first, in 1881, to conduct one of the experiments fundamental to disproving the existence of the luminiferous aether; this experiment would later be repeated by, among others, Michelson and Edward W. Morley, leading to the experiment becoming known as the "**Michelson-Morley Experiment**". Michelson's apparatus—an "interferometer"—takes a beam of light as input. The device splits it into two beams, directed at right angles to each other and one of which is parallel to the direction of motion of the Earth; these beams are then reflected back after a distance and recombined (see **Figure 10**). The recombination results in an interference pattern of light.

Figure 10
Diagram of the Michelson-Morley experimental apparatus showing the path of light along perpendicular axes



The two "arms" of the apparatus are then rotated so that the other beam is now parallel to the direction of the motion of the Earth, and the new interference pattern is compared to the initial interference pattern—hence why the apparatus is referred to as an *interferometer*. If there is, in fact, an aether through which light travels, we would expect to see a difference in the two interference patterns. However, this is **not** what we observe, despite the incredible sensitivity of the equipment and variety of repeated experiments. The motion of the Earth has no detectable effect on the speed of light, and so we can infer that the speed of light is the same in all directions.

A notable variation on the Michelson-Morley experiment was that conducted by Roy J. Kennedy and Edward M. Thorndike in 1932, appropriately known as the **Kennedy-Thorndike Experiment**. The apparatus is mostly the same, but one of the arms is shorter than the other. The difference in arm lengths means that the speed of the Earth itself affects the interference pattern of light the apparatus produces. No difference in the interference pattern was observed.

The results of this experiment suggest that, in addition to the speed of light being the same in all directions, the speed of light is also independent of the speed of the observer. These two facts together mean that the speed of light is constant in all frames of reference.

Albert Einstein did not base his theory of relativity directly on the disproval of the luminiferous aether and the confirmation that the speed of light is constant; instead, he based his theory on the postulate that the laws of physics are the same in all reference frames, and on the known fact that all (non-light) waves' speeds do not depend on the speed of their source.[71] However, the above experiments regarding the constancy of the speed of light provide historically relevant proof for Einstein's postulates, and proved that the constancy of a light wave's speed holds true even if light does not require a propagation medium.

4.1.2 SPECIAL RELATIVITY

The consistency of the speed of light in all frames of reference has consequences for how we describe space and time. These effects are impossible for us to perceive with our senses directly, as we move and operate at such a small fraction of the speed of light that the effects of relativity are negligibly small. Objects travelling at appreciable fractions of the speed of light, however—at "relativistic" velocities—experience a variety of strange effects that have, despite their strangeness, been verified experimentally.

If we, for the time being, ignore acceleration—which comes with another set of interesting consequences that I will discuss later—we can look at the "special" case of relativity, referred to as **special relativity.**

SIMULTANEITY, OBSERVERS, AND EVENTS

Two observers moving at relativistic speeds with respect to each other may experience the same "event"—something that occurs in a given place in space and time—*differently.* If a pair of events for Observer A occur at exactly the same time, they will generally not also occur at exactly the same time for Observer B.

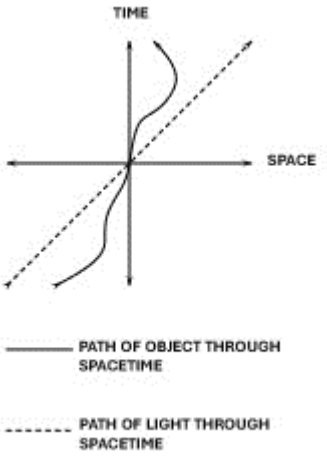
The theory of relativity emphasizes that there is no single "main" frame of reference, no stationary background against which all else can be measured, no single background grid against which the world can be built. Different observers may observe different versions of reality that are nevertheless each valid. We can visualize the differences in the placement of events within a pair of reference

[71] Their *frequency* might change, as seen with the Doppler Effect, but their *speeds* do not.

frames using a type of graph known as a Minkowski diagram.

For simplicity, let us assume that there is only one spatial dimension rather than three. Take a typical Cartesian plot, with the spatial coordinate on the x-axis and time on the y-axis. If we plot the motion of some object on this graph, we draw out the *history* of that object, or, in other words, its path through space and time. This graph is a **spacetime diagram** (see **Figure 11**). It depicts an object moving within one reference frame.

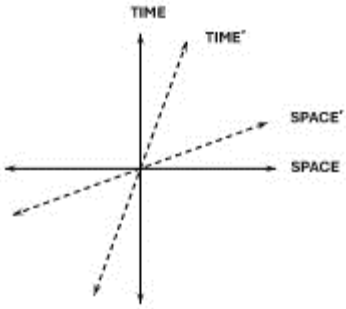
Figure 11
An example of a spacetime diagram showing the path of light and the path of an object through spacetime



A Minkowski diagram (see **Figure 12**) is a spacetime diagram with some modifications. Firstly, instead of time on the y-axis, the quantity ct is used; this is time multiplied by the speed of light, which gives a distance coordinate. The second modification is the inclusion of a second reference frame, with its origin at the same point as that of the original reference frame. If the two reference frames are moving at a high speed with respect to one another, the angle between the time and space axes of the second reference frame becomes smaller.

Spacetime diagrams are useful as a tool to visualize where an event in one reference frame occurs within a second reference frame, as well as to visualize more generally the morphing of space and time as observed between reference frames.

Figure 12
An example of a Minkowski spacetime diagram showing how one reference frame may appear distorted within another reference frame. The space and time axes of the second reference frame are denoted with a prime symbol.



THE LIGHT CONE

Because nothing can travel faster than the speed of light, the path that light takes through space and time provides a hard limit of what is possible. We can visualize this boundary. Take the origin point of a spacetime diagram to be our present location and time. Say we have a light bulb that emits light in all directions. If we draw out the paths that all the light takes on the spacetime diagram, it will form a triangular or conical shape, depending on if we draw the diagram with one or two spatial dimensions; this shape is called a **light cone** (see **Figure 13**).

The slope of the edge of the cone represents the speed of light. Any event within the cone ahead of us in time can be considered to be in our future; if we reflect the cone behind us in time, any event within the cone can be considered to be in our past. Beyond the boundaries of the cone are events that are impossible to reach due to the hard physical limit of the speed of light.

TIME DILATION

In addition to the boundary of what is possible to observe, the limit for all observers of the speed of light results in strange behaviour for the perception of time.

Imagine you're in a train travelling at close to the speed of light.[72] You have a lamp that can produce a single flash of light straight up at the ceiling, where there is a mirror. From your point of view, if you flash the lamp, the light will travel up to the mirror, then back down to the lamp, at the speed of light.

Someone looking through the windows at you, the lamp, and the mirror from the ground will observe what you're doing differently. Since the train you're on is *moving*, everything in it—you, the lamp, the mirror, *and the light*—is also moving, with respect to that person on the ground.

From the point of view of the person on the ground, the flash of light from the lamp has to travel not only up to the ceiling and back to the lamp, but also whatever distance the train has moved in the time it took the light to travel up and down: a distance a little greater than the distance *you* see the flash of light travel (see **Figure 14**).[73]

But the speed of light, for the person on the ground, is the same as the speed of light *you* observe, because the speed of light is the same for absolutely everyone. If the distances are different, but the speed is the same, the only way to reconcile this is that it is the *time* you and the person on the ground experience are different. You, on the train, experience time more slowly than the observer on the ground; this effect is referred to as **time dilation**.[74]

RELATIVISTIC DOPPLER EFFECT

Firstly, the wavelength of light is what determines its colour; shorter wavelengths of the visible spectrum of light are bluer, and larger wavelengths more red. We refer to the shortening of wavelength of light as blueshifting, and the lengthening of the wavelength of light as redshifting.

Say that there is a lamp traveling towards you, the observer, at close to the speed of light, emitting a constant stream of light. As the lamp moves towards you, it diminishes the distance between successive peaks and troughs

Figure 13
Diagrams of a light cone with one and two spatial dimensions showing the location of the futurue and past

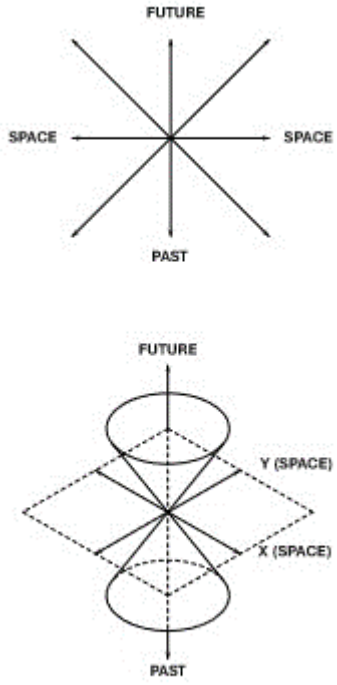
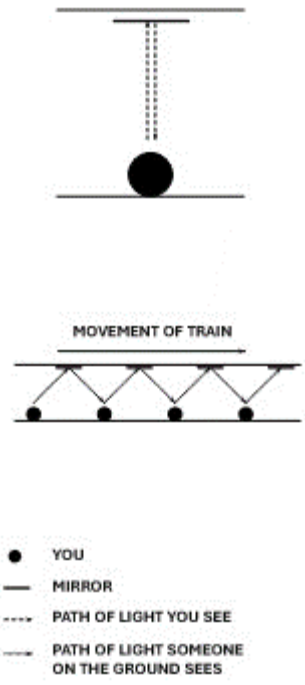


Figure 14
Time dilation as explained by the behaviour of light on a moving train as viewed by different observers



[72] Paul Allen Tipler and Ralph A. Llewellyn, *Modern Physics*, 6th ed (New York: W. H. Freeman and Co, 2012), 15.

[73] Tipler and Llewellyn, 31.

[74] Another, less architectural, explanation for time dilation is that if you run on the train in the same direction the train is moving, then your speed would exceed the speed of light. This implies that time must be running slower for you so that you do *not* exceed the speed of light.

of the light waves; in other words, it reduces the wavelength of the light. If instead the lamp is traveling away from you, the wavelength of the light will increase.

Time dilation is also a factor because the lamp is traveling at relativistic speeds. The time between peaks and troughs of the light waves that the observer measures is longer than the time that the lamp measures, but because the speed of light must remain the same for both, then the distance between successive peaks and troughs of the light waves from your point of view must also increase.

These factors together produce the **longitudinal relativistic Doppler Effect**.[75] Light sources traveling towards you appeared blueshifted, and light sources traveling away from you appear redshifted.

THE TWIN PARADOX

The strange behaviour of light and distance predicted by the theory of special relativity suggests that certain specific circumstances are paradoxical. One of the most commonly referenced such paradoxes is the **twin paradox**, which questions the behaviour of time dilation.[76]

Suppose that you have an identical twin, and that you are both wearing watches. You remain here on Earth, in what we shall think of as the "stationary" frame of reference, while your twin boards a spaceship that can travel near the speed of light and goes on a round trip from Earth to a distant star and back. When you and your twin meet again, you compare the time on your watches.

From your point of view, you have remained stationary and your twin has travelled. Thus, due to time dilation, your twin should have experienced their trip as taking a shorter amount of time than you did, and your watch reads as later than your twin's . However, from your twin's point of view, *you* have travelled while *they* have remained stationary. In this description, *you* have experienced a shorter amount of time than your twin, and your *twin's* watch reads a later time. Therein lies the paradox.

This particular paradox is solved by noticing that, importantly, to make a round trip your twin needs to have *turned around.* A change in direction means that your twin has accelerated.

[75] There is also a *transverse* relativistic Doppler effect, but I do not include it within this thesis.

[76] Tipler and Llewellyn, *Modern Physics*, 46–47.

Looking at the situation from your point of view presents no problems, because you are within a "stationary" frame of reference—you are free within the constraints of special relativity to observe what happens to any object, even if it accelerates. On the other hand, your twin *has* accelerated, even if only for a moment to turn around. Special relativity does not apply to reference frames that accelerate—accelerating reference frames is the doman of general relativity—and so the description of what your twin experiences above is incorrect and therefore presents no contradiction.

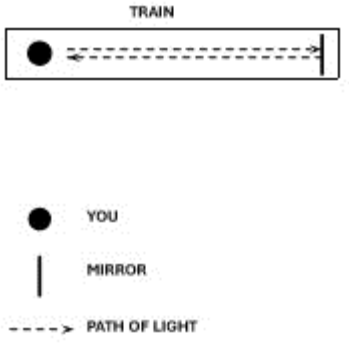
LENGTH CONTRACTION

As we have seen, time behaves differently when considering special relativity. Length, too, is measured differently between observers in different frames of reference.

Imagine you are again on a train, still travelling at close to the speed of light, but this time the lamp is at the back of the train facing forward and the mirror is at the front of the train.

To measure the length of the train while *in* the train, you can calculate the length of the train by standing at one end and timing the amount of time it takes for a flash of light to bounce back from a mirror at the other end of the train (see **Figure 15**). Flash the lamp, and you will observe the light travel from the lamp to the front of the train and back to the lamp, at the speed of light, as always. The length of the train is the speed of light multiplied by the time it took for the flash of light to return, divided by two.

Figure 15
Measuring the length of a train from inside the frame of reference of the train by using a flash of light



However, as discussed in the previous section, the time that you observe passing from within the train is different from the time someone standing on the ground outside the train observes. A stationary observer outside the train will see that time passes slower for you. The stationary observer then sees the light travel for a shorter amount of time than you do within the train.

The lengths, you calculate from inside and outside the moving train, therefore, are different. The stationary observer outside the train measures the length of the train to be slightly *shorter* than you measure it to be from inside the train. This phenomenon is referred to as **length contraction**.

LADDER PARADOX

The second common paradox in special relativity is the **ladder paradox**, which questions the behaviour of length contraction.[77]

Suppose that you are carrying a ladder horizontally, and that you can run at close to the speed of light. There is a barn with two open doors, one at each end. The ladder is twice as long as the barn. You want to see if length contraction can make the ladder fit inside the barn. To prove it, your friend is ready to shut each of the barn doors for just the instant the ends of the ladder pass the doorways.

You run carrying the ladder towards the front door, which is open. From the barn's point of view, the barn remains its usual length and the ladder shortens in length due to length contraction, thus having no problem fitting within the barn. However, from your point of view, the ladder is its usual length and the barn, due to length contraction, appears shorter—in this case, the ladder will *not* fit within the barn. This contradiction is the paradox.

The paradox is resolved by considering the motion of the ladder through the barn; its front end arrives at the barn before its back end. Remember that these two events may be perceived differently by you and the barn.

From the barn's point of view, the situation is as described above; the ladder travels fast enough that the front end of the ladder arrives at the rear door at the moment the back end of the ladder arrives at the front door. Your friend is able to shut both of the doors at the same time, which confirms that the ladder fits within the barn.

From your point of view, however, the situation is more complicated. The order of events, which can be worked out mathematically or using a Minkowski diagram, is different and completely unintuitive. First, the front of the ladder enters the open front door of the barn. The front of the ladder then exits through the rear door, and your friend shuts the front door for an instant. The back of the ladder then enters the reopened front door. The back of the ladder then exits the rear door, and your friend shuts the rear door for an instant.

Thus, from the point of view of you and the ladder, the ladder does not *need* to fit entirely within the barn for it to be possible for your friend to shut both of the barn doors simultaneously from *their* point of view—the brief shutting of

[77] Tipler and Llewellyn, 48–49.

the doors was not simultaneous for you and the ladder, and so you were able to pass through the barn.

MASS

It is not only time and space that stretch and contract at high speeds, but mass as well, in a way. The typical way that we think of mass—a measure of how much matter something contains—is referred to as **invariant mass** when discussing relativity. Different frames of reference measure the same value for invariant mass.

Relativistic mass, however, is a way of thinking about mass at high speeds. This quantity is different depending on the reference frame.[78]

Suppose that you are in a spaceship in what we will call the "stationary" reference frame, and that your friend is on another spaceship travelling at high speed with respect to you. You and your spaceships have the same mass. Imagine now that something—a gust of interstellar gas, perhaps—pushes both of the spaceships with the same amount of force at the moment your friend's spaceship passes yours. You will experience some amount of acceleration.

Because your friend is travelling at high speeds, they are experiencing the passage of time as slower. The amount of time the push takes, therefore, appears to your friend to take a shorter amount of time, and so the push will accelerate them *less* than the push accelerated *you*. This is, in a way, equivalent to if your friend and their spaceship had experienced an increase in mass such that it requires more force to accelerate.

4.1.3 GENERAL RELATIVITY

Einstein developed the *general* theory of relativity later on, expanding the special case of relativity with no consideration of acceleration to cases where acceleration is allowed. He postulated that gravity and acceleration are indistinguishable from each other; think of how the acceleration at the beginning of an elevator's movement makes you briefly feel as though you weigh more.

THE ORBITAL PRECESSION OF MERCURY

One of the early pieces of evidence supporting general relativity was the orbital precession of the planet Mercury. The amount of precession observed in Mercury's orbit was

[78] Jeffrey Bennett, *What Is Relativity? An Intuitive Introduction to Einstein's Ideas and Why They Matter* (New York: Columbia University Press, 2014), 106–7.

too large to be accounted for with purely the known objects in our solar system and the classical laws of physics. It was suggested that there was additional mass, perhaps in the form of an asteroid belt, whose additional gravitational effects would account for the irregularities in Mercury's orbit. However, with Einstein's general theory of relativity came an explanation that did not require unseen mass—the effects of the Sun's own gravitational well were enough to explain the anomalies, with startling accuracy.

GRAVITATIONAL LENSING

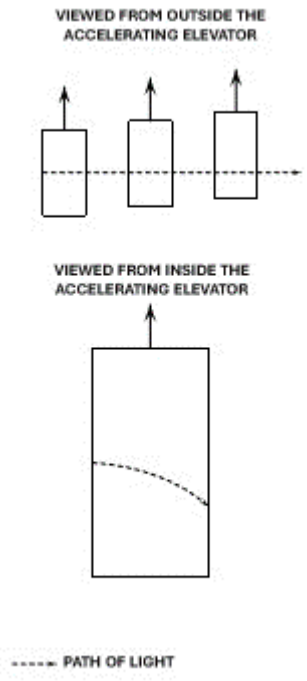
A consequence of gravity and acceleration being indistinguishable is the bending of light.

In 1687, Isaac Newton suggested that light might have mass and that it would behave like small amounts of matter; according to Newton's own theory of gravity, this would mean that light would bend toward large objects.[79] He was wrong in some ways—light has no mass—but his intuition that light is bent by matter has turned out to be correct via a different mechanism.

Imagine that you are in an elevator floating in space far from any mass and experiencing no gravity. There is a light on one wall of the elevator that can emit a flash of light horizontally. At the moment the light flashes, the elevator accelerates "upwards" in the direction of the top of the elevator. The flash of light continues to move horizontally as it did before, but by the time the light reaches the opposite wall of the elevator, the elevator has travelled "vertically" some distance. From your point of view inside the elevator, the path of the flash of light has curved slightly downward (see **Figure 16**).[80]

According to Einstein's gravity-acceleration equivalence principle, the accelerating elevator is equivalent to a stationary room experiencing an equivalent amount of gravity. A gravitational field, then, causes light to bend.

Figure 16
The effect of gravity on the path of light as explained through an elevator thought experiment. From inside the acceleraing elevator, light appears to take a curved path.



[79] Nathan Cohen, *Gravity's Lens: Views of the New Cosmology*, The Wiley Science Editions (New York: Wiley, 1988).

[80] Mathieu Rouaud, "Einstein's Elevator: World Lines, Michelson–Morley Experiment and Relativistic Paradox," *Physics* 4, no. 3 (August 11, 2022): 892–911, https://doi.org/10.3390/physics4030058.

The presence of matter warps the path that light follows. Given enough mass and the right angle, it is possible for light from *behind* a massive object to reach us because its path is warped by gravity to skirt around the obstruction (see **Figure 17**). This phenomenon is referred to as gravitational lensing, because the huge amount of gravity acts like a lens refracting light.

Gravitational lensing produces some remarkable effects. If two large masses, such as a pair of stars or a star and a galaxy, are perfectly along the same line of sight so that one is hidden behind the other, the gravitational lensing effect will smear the obstructed star's light into a ring around the obstructing star. If the stars are not quite, but close to, perfect alignment, the obstructed star may appear as a pair of crescents around the obstructing star. Even a pair of poorly aligned massive bodies can result in, for example, multiple images of the same galaxy arrayed around a star (see **Figure 18**).

Figure 17
The curvature of spacetime produced by a large mass affecting the direction of light and producing gravitational lensing

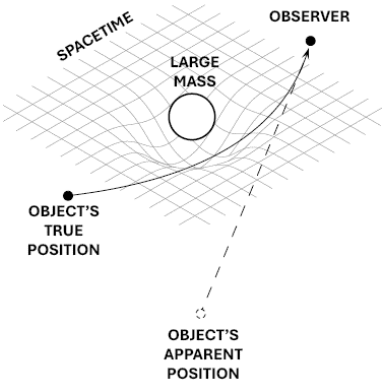


Figure 18
Rings of Relativity (2020) by ESA/Hubble & NASA, S. Jha

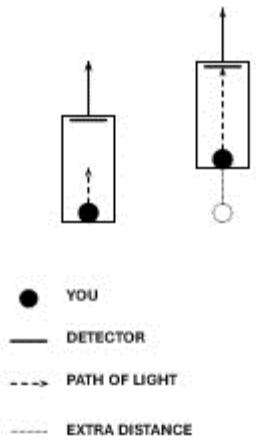


GRAVITATIONAL REDSHIFT

When gravity is strong enough, it can even discernibly affect the colour of light. Because gravity and acceleration are functionally equivalent, we can use our understanding of how acceleration would affect light to imagine how *gravity* would affect light.

Imagine that you are in an elevator floating in space far from any mass and experiencing no gravity. The elevator, through whatever means, is able to accelerate in the direction of the top of the elevator so that you feel a force indistinguishable from gravity pulling you towards the bottom of the elevator. Flash your flashlight towards the detector at the top of the elevator. In the time it takes for *this* flash of light to reach the detector, the acceleration of the elevator will have moved the top of the elevator slightly farther away from its starting position (see **Figure 19**). The flash of light, then, must travel a slightly *longer* distance to reach the detector, just as we see with Doppler shifts. In other words, the wavelength of this flash of light is slightly longer and its colour is therefore shifted towards the red end of the light spectrum.

Figure 19
Gravitational redshift as explained through an elevator thought experiment. The acceleration of the elevator means that light needs to travel further, resulting in a longer wavelength and a redder colour.



According to Einstein's gravity-acceleration equivalence principle, the accelerating elevator is equivalent to a stationary room experiencing an equivalent amount of gravity. A gravitational field, like the acceleration of the elevator, will cause a **gravitational redshifting** of light.

An alternative intuitive explanation for gravitational redshift describes the effect in terms of energy gain and loss. Consider a single photon near a massive object, say a black hole. If it is moving away from the black hole, it will expend energy to do so. A loss in energy means that the frequency of the photon will decrease, which is equivalent to saying that its wavelength increases; if its wavelength increases, that means that its colour moves towards the red end of the light spectrum.[81] This effect is called **gravitational redshifting**. Similarly, a photon moving towards the black hole would *gain* energy, increasing its frequency and decreasing its wavelength; this effect is called **gravitational blueshifting**.[82]

[81] Prabhakar Gondhalekar, *The Grip of Gravity: The Quest to Understand the Laws of Motion and Gravitation* (Cambridge ; New York: Cambridge University Press, 2001), 163.

[82] Fran De Aquino, "Gravitational Blueshift and Redshift Generated at Laboratory Scale," n.d.

GRAVITATIONAL TIME DILATION

General relativity, like special relativity, results in the unusual behaviour of time.

Consider a different elevator. You are, like before, at the bottom of the elevator with a flashlight. This time, however, there is a chair at the top of the elevator in which your friend is sitting. They, likewise, have a flashlight. Both of you turn your flashlights on and off at a rate of once per second.[83]

When the elevator is at a standstill, you both observe that the rate of the two lights' flashing is once per second. However, you observe otherwise when the elevator accelerates "upwards." When the elevator accelerates, you and your friend move "upwards" from the locations at which each of your flashlights emitted their flashes. You therefore move *towards* the light from your friend's flashlight, meaning the light needs to travel a *shorter* distance to reach you. Your friend, on the other hand, moves *away* from the light from *your* flashlight, meaning the light needs to travel *farther* to reach your friend.

You therefore observe the rate of flashing of your friend's light as faster than once per second, and your friend observes the flashing of your light as slower than once per second.

Because we already know that the speed of light must remain the same for everybody, this means that time itself must be stretching or compressing to accommodate the change in the distance the light travels. Time passes slower for you than it does for your friend.

When we turn the nebulous acceleration of the elevator back into terms of gravity, the change in observed time still applies because gravity and acceleration are indistinguishable. We can describe your friend as being high up in, say, a planet's gravitational field, while you are low down in that same planet's gravitational field. This means that the higher you are in a gravitational field, where the gravitational strength is lower, the slower time passes, and conversely that the lower down you are in a gravitational field, where gravitational strength is higher, the faster time passes. This is called **gravitational time dilation.**

[83] Bennett, *What Is Relativity? An Intuitive Introduction to Einstein's Ideas and Why They Matter*, 245–46.

NON-EUCLIDEAN GEOMETRY

In the previous elevator example, you observe a different colour of light than the detector does. Because you are holding the flashlight and therefore see the flash at the exact moment it is emitted, you see the light emitted as the colour it is *without* the gravitational redshift that the detector sees. This means that gravitational redshifting is not compatible with a "normal" geometry of space, in which two observers within the same reference frame must observe the same wavelength of light.[84]

The geometry of space-time, then, must be different. It is not flat, but is instead *curved*. The presence of mass distorts the fabric of space-time, and we experience that distortion as gravity. We can picture this distortion in two dimensions as dropping, say, a bowling ball into a rubber sheet. The sheet stretches to accommodate the bowling ball. A baseball rolling across the sheet, if it passes by close enough, will get caught in the dent made by the bowling ball and its path will curve.

The type of geometry that describes this behaviour is a type of **non-Euclidean geometry**—non-Euclidean because it deals with curved surfaces rather than the flat planes used by Euclidean geometry as discussed in **Chapter 2**.

GRAVITATIONAL WAVES

The changes in the shape of spacetime are difficult, but not impossible, to measure. Einstein's initial formulation of general relativity predicted that mass, when accelerated, would produce ripples in space-time. These are called **gravitational waves**. A truly staggering amount of mass is required to produce gravitational waves detectable by measurement equipment on Earth. The first detected gravitational waves, measured by physicists at the Laser Interferometer Gravitational-Wave Observatory in California in 2015, were produced by the merging of a pair of black holes.[85]

Gravitational waves are detected with an apparatus similar to that used in the Michelson-Morley experiment: two arms, kilometres long, oriented perpendicular to each other. A beam of light is sent out from the central point along each of these arms and reflected back by mirrors. The length of the arms is the same, so the beams should

[84] Jose Natario, *General Relativity Without Calculus: A Concise Introduction to the Geometry of Relativity* (Berlin, Heidelberg: Springer Berlin Heidelberg, 2011), 61, https://doi.org/10.1007/978-3-642-21452-3.

[85] "LIGO Celebrates First Anniversary of Historic Gravitational Wave Detection!," LIGO Lab | Caltech, accessed May 14, 2024, https://www.ligo.caltech.edu/news/ligo20160914.

return back to the detector at the central point in exactly the same amount of time. The two waves of light will then cancel each other out.

However, when a gravitational wave passes by, the length of the two arms will change, one becoming longer and the other becoming shorter, and then the reverse, repeating as the wave passes. The beams of light will travel different distances due to the changing lengths of the arms. When the light waves return to the detector, they will *not* cancel out, and instead will form an interference pattern.[86]

BLACK HOLES

Gravitational waves, as stated, can be produced by black holes. These were one of the predictions of general relativity and have since been widely studied.

In 1939, American physicist J. Robert Oppenheimer and his student Hartland Snyder published a paper suggesting that an object with a large enough density would warp space-time to such an extent that nothing would be able to escape from its gravitational pull, not even light.[87] Light's inability to escape gave this object its name: a **black hole**.

When a star with enough mass reaches the end of its life and stops being able to sustain nuclear fusion, there remains no outward force to counteract the strength of the inward gravitational force produced by the star's immense mass. Gravity will then cause the star to collapse in on itself, shrinking the volume that the star occupies until the star's density occupies, essentially, a single point in space.

DARK MATTER

When we observe the motions of celestial objects on a large scale, like when we look at the density of stars within a galaxy, we notice behaviour inconsistent with what would be expected according to gravitational laws and the amount of mass we are able to detect. The amount of luminous mass—mass that we can detect with light—and gravitating mass—mass whose presence we can infer due to gravitational interaction with objects we can see—are different. The universe is made up *primarily* of this

[86] "FAQ," LIGO Lab | Caltech, accessed May 14, 2024, https://www.ligo.caltech.edu/page/faq.

[87] Tipler and Llewellyn, *Modern Physics*, 108–9.

"dark" matter; it is estimated that around 85 percent of the matter in the universe is dark matter.[88]

There are numerous hypotheses about the nature of dark matter. One possibility is that dark matter is partially composed of small black holes; these do not emit electromagnetic radiation and do interact gravitationally. These could, perhaps, be detected via the gravitational lensing of visible objects behind them. Another possibility is small, cold, dense clouds of gas; however, these would be likely to accumulate with each other and form larger, more easily detectable clouds of gas. Another is brown dwarfs, which are star-like objects that did not accumulate enough mass to kickstart the nuclear fusion process required to form true stars.[89]

Other possible explanations for dark matter will be discussed later in Chapter 5.1.5.

4.2 HIERARCHY AND THE OBSERVER

UNIVERSAL LAWS

The theory of relativity has at its core the idea that there is no single privileged point of view. The world that relativity describes is one in which two separate observers can witness the same event, *disagree* about what that event looks like, and they can *both still be correct*. Relativity, too, emphasizes the requirement that all observers experience the same physical laws, even if that means their perception of another observer's world—their time, their length—must stretch or compress to accommodate that.

There is no longer a single great power that organizes the universe, but instead a series of fundamental rules that everyone must follow. Additionally, the hierarchy of the cosmos is flattened not only by relativity's emphasis on the consistency of fundamental laws for all observers, but also by the viewpoints of different observers being hierarchically equivalent.

[88] Beatriz Gato-Rivera, *Antimatter: What It Is and Why It's Important in Physics and Everyday Life* (Cham: Springer International Publishing, 2021), 65, https://doi.org/10.1007/978-3-030-67791-6.

[89] Ken Freeman and Geoff McNamara, *In Search of Dark Matter*, Springer-Praxis Books in Popular Astronomy (Berlin ; New York : Chichester, UK: Springer ; Published in association with Praxis Pub, 2006), 118.

We can see the idea of universal laws in art. One example is that of Theo van Doesburg, a Dutch artist who had an interest in science and explicitly took inspiration from Einstein's theory of relativity, although his interest in the wider idea of relativity existed before he encountered Einstein's theory in the early 1920s.[90] Van Doesburg referred to his art style—including his use of oblique angles instead of fellow Dutch artist Piet Mondrian's use of orthogonality—as "Elementarism," a term which he said related to his interest in the mutability of spacetime, [91] and a term which I suggest evokes the idea of fundamental laws.

Van Doesburg's paintings have no particular hierarchical organization.[92] For example, his piece *Contra Construction* (see Figure 20) uses planes to create spatial relationships without closing any space off from the rest or prioritizing any particular space or view.

Figure 20
Contra Construction (1923) by Theo van Doesburg. Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY. The planes create spatial relationships without closing any space off from the rest or prioritizing any particular space or view.



The reduction of the cosmological hierarchy can also be seen in art that explores simultaneity: differing perspectives, neither of which is given an inherent priority. We see the concept of simultaneity arise in art movements like Cubism and Futurism in the early twentieth century.[93] A Cubist painter of the time, Guillaume Apollinaire, explicitly described Cubist art as invoking "simultaneity," [94] and we see the Italian painter Umberto Boccioni invoke it in titling his c. 1912 painting *Simultaneous Visions* (see **Figure 21**). However, American art historian Linda Henderson notes that art movements like Cubism were more likely influenced by earlier scientific ideas than Einstein's theory of relativity, given the publication dates of Einstein's works.[95] I believe that ideas within the general zeitgeist influence both science and art, rather than it being the case that science and art necessarily *directly* influence each other.

Figure 21
Simultaneous Visions (c. 1912) by Umberto Boccioni. The overlapping forms and scenes imply simultaneity of events.



THE SPHERE OF THE OBSERVER

Like the advent of the heliocentric universe, the discovery of relativity changed our place in the universe as the observer. This time, instead of being removed from the centre and placed offset from the centre, we were placed back in the centre—but only in the sense that we can only

[90] John G. Hatch, "Some Adaptations of Relativity in the 1920s and the Birth of Abstract Architecture," *Nexus Network Journal* 12, no. 1 (April 2010): 136, https://doi.org/10.1007/s00004-010-0024-6.
[91] Hatch, 136.
[92] Hatch, 142.
[93] Brittany Myburgh, "Space-Time and Utopia: Notes on Artistic Engagement with Physics from Cubism to Laszlo Moholy-Nagy," 2022.
[94] Myburgh, 56.
[95] Myburgh, "Space-Time and Utopia: Notes on Artistic Engagement with Physics from Cubism to Laszlo Moholy-Nagy."

observe things from our point of view. Even the simultaneity of events, something previously taken as straightforward and common sense, now depend on where and when you exist.

This brings back to geometry the importance of the sphere, but instead of the sphere being held up as a shape that is important for its perfection, the sphere is simply the shape of what we can see of the universe, extending from our point of view in time and space. American architect Buckminster Fuller describes this as, "the radiating spheres whose wave lengths are attuned to our wave length receptivity of consciousness."[96]

The centre of the universe has been made conditional, and that there is now not a single centre, but an infinite number of centres.

4.3 FORCE AND MATTER

Figure 22
Unique Forms of Continuity in Space (1913) by Umberto Boccioni. Photo: Wmpearl. License: Public domain. The form of the statue appears warped as if subject to drag as it moves.



WARPING

The since-disproven luminiferous aether had an impact on art. The concept of a medium that can produce drag can be seen in art such as the statue *Unique Forms of Continuity in Space* by Italian artist Umberto Boccioni (see **Figure 22**).

The general theory of relativity further emphasizes the idea that force—gravity—can warp matter. While the discovery of gravity during the Scientific Revolution was expressed in the warping of shapes in Baroque architecture, gravity's effect on the perception of matter was not as extensive as it became after the formulation of general relativity. Gravity, or some other force, could act in any direction and not only towards the centre of the Earth, and could pull both matter, light, and space itself.

Art exists that expresses the idea that objects, and not just the Earth and planets, could exert gravity. The painting *The Poet and the Painter* by Italian artist Giorgio de Chirico (see **Figure 23**) depicts a room in which objects, despite the size of the room, are tightly clumped together, as if attracted gravitationally together.[97]

[96] William W. Braham, Jonathan A. Hale, and John Stanislav Sadar, eds., *Rethinking Technology: A Reader in Architectural Theory* (London ; New York: Routledge, Taylor & Francis Group, 2007), 43.

[97] Tracey Eve Winton, conversation with author, May 29, 2023.

A clear example of the way a force could be imagined to push and pull architectural forms is the Einstein Tower in Potsdam, designed by Prussian architect Erich Mendelsohn in the early twentieth century (see **Figure 24**). He learned about Einstein's recent—and at the time, still unproven—theory of relativity through his acquaintance with the astrophysicist Erwin Finlay-Freundlich, who eventually contracted Mendelsohn to design a facility in which to conduct experiments with the Sun's spectra in the hopes that it would provide evidence relating to relativity.

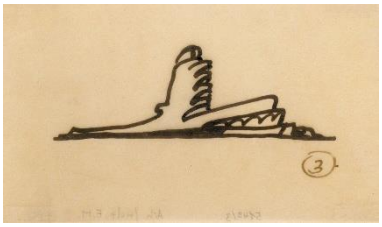
While Mendelsohn's earliest sketches depicted a building concept that was purely practical, later changes to his design took direct inspiration from the principles of relativity itself. Particularly, he sought to express the concept that mass and energy are interchangeable by shaping the building as a wavelike form that pushes and is swept back across the landscape: in a 1923 lecture, he says, "Ever since science has come to realize that the two concepts matter and energy, formerly kept rigidly apart, are merely different states of the same primary element, that in the order of the world nothing takes place without relativity to the cosmos, without relationship to the whole…"[98]

The view of the material of the world around us being mutable continued even with the disproval of the aether. The disproval of the aether was followed by the stranger idea of relativity, which turned space itself into something that can warp. This was a great contrast with the early Newtonian conception of space, which was a "logically imperfect absolute view of space and time,"[99] as described by the eighteenth-century German philosopher Gottfried Wilhelm Leibniz.

Figure 23
has been removed due to copyright restrictions.
It was the painting *Poet and Artist* (1975) by Giorgio de Chirico. The objects in the painting are grouped together as if gravitationally attracted.

Original source: Giorgio de Chirico. *Poet and Artist*. 1975. Oil on canvas, 100 x 81 cm. The Foundation Giorgio and ISA de Chirico, Rome. https://fondazionedechirico.org/collezione/#pittura.

Figure 24
Sketch of Einstein Tower (1920) by Erich Mendelsohn. Image from Staatliche Museen zu Berlin, Kunstbibliothek. The building is a wavelike form that appears to sweep across the landscape.



4.4 SPACE, TIME, AND MOTION

THE VOID

The concept of space as a void in which activity occurs became more widespread in the early twentieth century. There is, for example, a shift in architecture towards thinking of void spaces, or volumes, determining the

[98] Erich Mendelsohn, Regina Stephan, and Charlotte Benton, eds., *Eric Mendelsohn: Architecture, 1887-1953* (New York: Monacelli Press, 1999), 31.
[99] Lee Smolin, *Three Roads to Quantum Gravity*, Science Masters (New York, N.Y: Basic Books, 2002), 37.

placement of the solid walls rather than solid walls, or masses, creating volumes of space.[100]

August Schmarsow, an art historian and architectural theorist during the late 1800s and early 1900s, proposed that space, and not only form, ought to be thought of as a major characteristic of architecture.[101] Schmarsow posited that humans relate to architecture primarily in the way in which we move through architecture—in other words, that humans relate to architectural *void*.

Admittedly, Schmarsow discussed his ideas about space in a lecture he gave in 1893, several years before Einstein formulated his theory of relativity. I am not suggesting that relativity directly influenced Schmarsow's thinking, as that would be impossible given the timeline of events, only that these ideas about space in different disciplines arose at similar points in history. Interestingly, however, Schmarsow was a proponent of the use of a more scientific approach to art and architecture.[102]

Some years later, in 1943, architectural historian Bruno Zevi published his book *Verso un'architettura organica* in which he also argues for space rather than form being the primary component of architecture.[103] Unlike Schmarsow, Zevi disagreed with applying scientific methods to architecture, saying that it reduces a building to "a machine for producing certain predetermined human reactions."[104]

WARPING THE CONTAINER

The biggest impact of the theory of relativity on how we view space is the idea that space itself is mutable: that not only matter within space can be stretched and warped, but that the shape of the container itself can change.

The warped geometry of the Baroque, such as ovals being used instead of perfect circles, was related to the then-new centre of the universe—the Sun— being offset from the old centre of the universe—the Earth. It was more about the flattening of the existing hierarchy and the associated move away from idealized geometric perfection. On the other hand, the warping of geometry in relativity is about space undergoing a *process of change*, the resulting shape

[100] Charles W. Millard, "Modernist Architectural Space," *The Hudson Review* 20, no. 3 (1967): 449, https://doi.org/10.2307/3849762.
[101] Johanna Gullberg, "Voids and Bodies: August Schmarsow, Bruno Zevi and Space as a Historiographical Theme," n.d., 1.
[102] Gullberg, 3.
[103] Gullberg, 6.
[104] Bruno Zevi, *Architecture as Space: How to Look at Architecture*, ed. Joseph A. Barry and Milton Gendel (New York: Horizon Press, 1957), quoted in Gullberg, 7.

of the space, in relativity, is less important than the fact that the shape used to be something else or is something else from a different point of view. The resulting change in geometry from the discovery of heliocentrism and from the theory of relativity may be the same, but the motivations behind them are different. The theory of relativity introduces *change*.

In the early twentieth century there were artists who expressed an enthusiasm for conveying change or the passage of time in their work. Van Doesburg, for example, had an interest in coupling time and space in art and architecture.[105] He explicitly compared his art style Elementarism to relativity, and elaborated that he saw it as an expression of life continually changing.[106]

Swiss artist Paul Klee evoked cosmological change, although not change expressly connected to relativity, in his piece *Genesis of the Stars* (see **Figure 25**).[107] Painted in 1914, the work is partially based off of the Hertzsprung-Russell diagram (see **Figure 26**) published that same year, which describes the colour of stars in relation to their temperature, as well as the evolution of stars over their lifespans. The title, and the Bible verse *1 Moses 1:14* written near the bottom that references the German Bible's equivalent of the Book of Genesis, refer clearly to the idea of change on a grand scale.

French philosopher Gaston Bachelard wrote and disseminated a summary of the new cosmology proposed by Einstein in 1934.[108] This summary was widely read by Surrealists, and its influence on Surrealist art is clear. The warping of time is present symbolically in Surrealist painter Salvador Dalí's work's use of "melting" watches, most famously known from his painting *The Persistence of Memory* (see **Figure 27**). Dalí himself described the watches as a metaphor for the relativity of time[109] and as

Figure 25
Genesis of the Stars (1914) by Paul Klee. The lines are partly based off of the Hertzsprung-Russell star evolution diagram, which shows an interest in change over time on a grand scale.

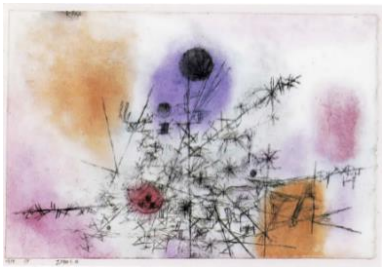


Figure 26
The Hertzsprung-Russell diagram. Image by Richard Powell. License: CC BY-SA 2.5. The diagram shows the colour of stars in relation to their temperature. Star temperature is correlated with stages of stellar evolution.

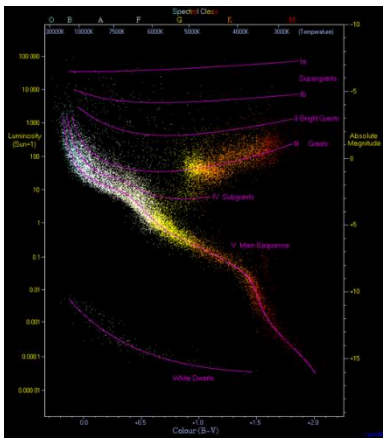


Figure 27
The Persistence of Memory (1931) by Salvador Dalí © Salvador Dalí, Fundació Gala-Salvador Dalí, VEGAP / CARCC Ottawa 2024. Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY



[105] Hatch, "Some Adaptations of Relativity in the 1920s and the Birth of Abstract Architecture," 137.
[106] Hatch, 145.
[107] Gamwell and Tyson, *Exploring the Invisible*, 251.
[108] Gamwell and Tyson, 261.
[109] Gamwell and Tyson, 261.

Figure 28
Kinetic Construction: Standing Wave (1919-20, replica 1985) by Naum Gabo. Tate, presented by the artist through the American Federation of Arts 1966. The Work of Naum Gabo © Nina & Graham Williams / Tate, 2020. Photo: © Tate. Empty space is expressed through the implied volume created by the oscillating metal bar. Time is expressed by the motion itself.



Figure 29
has been removed due to copyright restrictions.
It was the painting *Piazza* (1913) by Giorgio de Chirico. The painting uses stiff, geometrical forms that make time appear frozen. The plume of steam rises directly upwards from the locomotive in the rear of the image, implying that the train is stationary.

Original source: Giorgio de Chirico. *Piazza*. 1913. Paint on canvas, 51.5 x 75.5 cm. Fondo Nacional de las Artes. https://www.bellasartes.gob.ar/en/collection/work/7227/.

"the extravagant and solitary [melting] Camembert of time and space."[110]

Cubist artists' use of ambiguous, overlapping perspectives evoked the same object at different points in time.[111]

Russian sculptor Naum Gabo used the theory of relativity's merging of space and time in his sculpture *Kinetic Construction: Standing Wave* (see **Figure 28**). While the sculpture, a metal bar oscillated by an electric motor, is a literal standing wave, a topic in physics that is not exclusive to relativity, Gabo's intention was to express space through the implied volume of the oscillating metal bar and time through its motion.[112]

Furthermore, Italian artist Giorgio De Chirico's paintings have an unusual sense of stillness that emphasizes the quality of time, in contrast to the Futurist art movement's interest in motion and dynamism.[113] His paintings are mostly devoid of people despite depicting public spaces, and his paintings use stiff, geometrical forms that evoke frozen motion rather than dynamic motion. Both of these characteristics can be seen in his painting *Piazza* (see **Figure 29**). Additionally, in *Piazza*, there is a steam locomotive in the distant background whose plume of smoke is, curiously, rising straight up rather than trailing behind it as it moves—this detail implies that the train is stationary.[114]

Other artists interpreted time as a fourth dimension more generously, and instead imagined the fourth dimension as an extra spatial dimension instead. Higher-dimensional space more generally was of deep interest to mathematicians such as Carl Friedrich Gauss and Bernhard Riemann in the 1800s, and four-dimensional space escaped from the

[110] "Les Pleurs d'Héraclite," in *La Conquête de l'irrationel* (Paris: Editions Surréalistes, 1935), 25, quoted in Linda Dalrymple Henderson, *The Fourth Dimension and Non-Euclidean Geometry in Modern Art*, Revised edition, Leonardo Book Series (London, England ; Cambridge, Massachusetts: The MIT Press, 2013), 500.

[111] T. Bellone, F. Fiermonte, and L. Mussio, "The Common Evolution of Geometry and Architecture from a Geodetic Point of View," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-5/W1 (May 16, 2017): 629, https://doi.org/10.5194/isprs-archives-XLII-5-W1-623-2017.

[112] Gamwell and Tyson, *Exploring the Invisible*, 281.

[113] Markus Brüderlin et al., eds., *The Art of Deceleration: Motion and Rest in Modern Art from Caspar David Friedrich to Ai Weiwei* (Ostfildern: Hatje Cantz, 2011).

[114] Winton, conversation with author, May 29, 2023.

hard sciences into wider popularity in the second half of that century due to its association with spiritualism.[115]

While this fourth spatial dimension in art is not necessarily the same as the fourth dimension of relativity, which is time, there remains an underlying sense that there are aspects of the universe that we cannot sense. Even when a fourth spatial dimension is not being conflated with the fourth dimension of time, it is not easy to convey time in static art because we inherently experience time in a different way than we do the spatial dimensions. Maurice Maeterlinck, a Belgian writer in the early half of the twentieth century, expressed difficulty with "spatializing" time, saying that "time, for want of a better explanation… [is] movement of space, and space as the rest of time… caught between space and time, we end in some kind of cosmic cul-de-sac."[116]

An example of early twentieth century art that demonstrates clearly the interest in dimensions beyond the typical three spatial directions are the works of Russian Suprematist painter El Lissitzky.[117] His series of *Proun* paintings use combinations of geometrical shapes—including non-Platonic shapes like parabolas and hyperbolas—as well as distorted grids that suggest perspective or warped space. El Lissitzky explicitly drew on contemporary science as inspiration: his work *Proun G7* (see **Figure 30**) mimics the shape of a Minkowski spacetime diagram.

Lissitsky's work also demonstrates an artistic interest in the depiction of time in still images. Lissitsky's *Proun 93: Free-Floating Spiral* (see **Figure 31**), for example, evokes movement. The lines of the spiral, much like a diagram of the Doppler effect, shift as if their source is moving. The spiral also looks like a cone, but it is unclear in which direction it is pointing.[118] This creates the sense of movement in space even in a flat image.

Figure 30
Proun G7 (1923) by El Lissitzky. The shape of gaps between areas of colour is reminiscent of a Minkowski spacetime diagram.

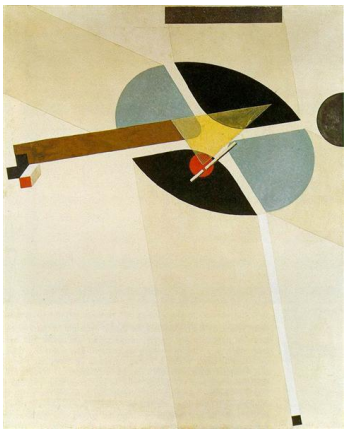
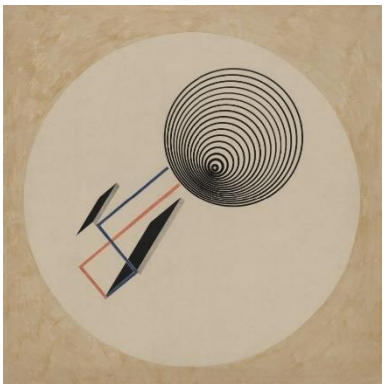


Figure 31
Proun 93: Free-Floating Spiral (c. 1923) by El Lissitsky. The shifting lines of the spiral imply movement.



[115] Christoph Lehner, Jürgen Renn, and Matthias Schemmel, eds., *Einstein and the Changing Worldviews of Physics* (Boston: Birkhäuser Boston, 2012), 139, https://doi.org/10.1007/978-0-8176-4940-1.
[116] Maurice Maeterlinck, *Die Vierte Dimension* (Leipzig: Deutsche Verlags Anstalt, 1929), quoted in Lehner, Renn, and Schemmel, 140.
[117] Lehner, Renn, and Schemmel, 140.
[118] Hatch, "Some Adaptations of Relativity in the 1920s and the Birth of Abstract Architecture," 137–38.

5 QUANTUM MECHANICS

5.1 CONTEXT

Quantum mechanics is a theory of modern physics that, unlike the theory of relativity, deals with the universe at a miniscule scale. It explains the behaviour of atoms and the particles that make up atoms.

There are a few early concepts in modern physics that led directly to the development of quantum mechanics:

1. **Blackbody radiation**: the behaviour and distribution of the energy given off by hot objects.
2. **The photoelectric effect**: the emission of particles from a surface underneath a beam of light.

Quantum mechanics itself has three fundamental concepts:

1. Heisenberg's uncertainty principle
2. The Pauli exclusion principle
3. Wave-particle duality

In addition to these fundamental concepts, physicists have come to a general consensus regarding the hierarchy and composition of a number of experimentally verified particles and forces; this model is referred to as the **Standard Model**.

The theories examined in this chapter of the thesis form only a small slice of all the details and theories of quantum mechanics as it is an astoundingly broad topic. I have endeavoured to include the most fundamental concepts of quantum mechanics, as described above, but I have also decided to include some concepts that I believe offer a more varied range of implications for the structure of the universe rather than focussing on those which offered further *depth* to existing ideas. This is because this thesis aims to explore the array of possible differences in cosmology as expressed by architecture. I have therefore chosen to include models that further explore the Standard Model and a number of models of particle physics that go *beyond* the Standard Model, even though they may lack experimental evidence. The concepts I have chosen to include are:

PARTICLES EXTENDED

1. Quantum chromodynamics
2. Preon models
3. Entanglement

SYMMETRIES

1. The gauge principle
2. Supersymmetry
3. The Georgi-Glashow model & SU (5)

WEIRD MATTER

1. Antimatter
2. Dark matter

5.1.1 FOUNDATIONAL CONCEPTS

RADIATION

We use the word "light" in everyday language to refer almost exclusively to visible light. However, the same light that we can see also exists as colours beyond the range of natural human perception. Newton split white light into its component colours, and in the early 19th century, other physicists added new colours entirely.

In 1800, German-English physicist William Herschel placed a newly technologically-improved mercury thermometer near a band of light whose colours were split apart by a prism. The temperature he measured rose when he passed the thermometer through the various colours of visible light; however, it also rose when Herschel held the thermometer *past* the visibly red light. He had discovered the first electromagnetic waves that cannot be seen by the human eyes, and called this part of the light spectrum the **infrared**.[119]

In 1895, German physicist Wilhelm Röntgen was conducting an experiment where he passed a high-voltage electric current through a glass tube evacuated of air. The current would produce electrons from the little gas remaining in the tube. The tube was covered in opaque cardboard to protect parts of the equipment from these generated electrons. The experimental apparatus also included a chemical-coated paper screen. Röntgen noticed that this screen, despite being supposedly shielded from anything occurring within the tube, would fluoresce while he was conducting his experiment. The fluorescence, it turned out, was caused by the emanation of high-energy light that

[119] Manjit Kumar, *Quantum: Einstein, Bohr and the Great Debate about the Nature of Reality*, 1. American ed (New York, NY: Norton, 2010), 21.

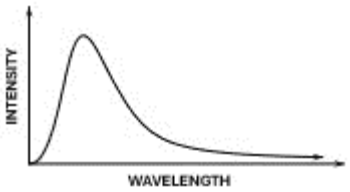
could pass *through* the otherwise opaque cardboard.[120] Light at this part of the spectrum—beyond violet—is now referred to as **x-rays**.

The discoveries of both the infrared and x-rays were the beginning of a trend in physics to uncovering properties of the universe that cannot be seen directly but can be observed through other means. X-rays, for instance, can be used to photograph the interior of the human body, the painted-over layers in artwork, or below the surface of other objects to reveal hidden information.

BLACKBODY RADIATION

Light hitting an object is either reflected or absorbed. A **blackbody** is a hypothetical object that reflects no light—hence the name —and instead absorbs all light. The light heats the blackbody, like it would any object, and the blackbody radiates this heat back out at all wavelengths of light. Plotting the amount of radiation against wavelength produces a blackbody spectrum (see **Figure 32**). The peak of this spectrum is dependent only on the blackbody's temperature; this is why hot objects, like the coils of stoves or pottery being fired, follow the same range of colours in the same order when they begin to glow with heat, from red-hot to white-hot, with orange and yellow in between.

Figure 32
The shape of a typical spectrum of blackbody radiation

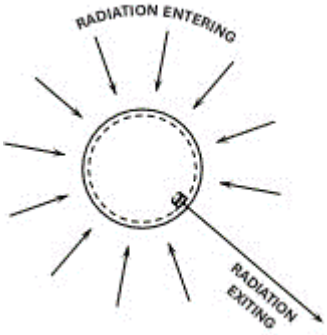


This phenomenon can be described mathematically. The Rayleigh-Jeans Law is a mathematical approximation of the intensity of electromagnetic radiation as a function of wavelength of a blackbody of a given temperature. It' is a decent approximation for large wavelengths, and an exceptionally poor approximation at short wavelengths, where it predicts infinite energy. This unfortunate phenomenon was described as the ultraviolet catastrophe: an ideal blackbody at thermal equilibrium would radiate infinite energy at *ultraviolet* wavelengths.

[120] Arati S. Panchbhai, "Wilhelm Conrad Röntgen and the Discovery of X-Rays: Revisited after Centennial," *Journal of Indian Academy of Oral Medicine and Radiology* 27, no. 1 (2015): 90, https://doi.org/10.4103/0972-1363.167119.

A perfect blackbody does not exist, although some objects, like stars, approximate a blackbody quite well. Around the turn of the twentieth century, German physicist Max Planck imagined a conceptual blackbody as a hollow sphere whose interior surface is covered with massless springs of varying stiffnesses, with a single small hole in its surface[121] (see **Figure 33**). Any light that passes through the hole into the interior of the sphere will bounce around inside until it is absorbed and heats the interior of the sphere. The sphere also acts as a perfect emitter of all wavelengths of radiation, since the wavelength of any radiation that escapes from the hole will be representative of the distribution of wavelengths inside the sphere.

Figure 33
Planck's conceptual blackbody. All wavelengths of are absorbed and then radiated back out at all wavelengths through a tiny hole.



The hypothetical massless springs would oscillate at set frequencies, and they would be "switched on" based purely on temperature, and no other factor. Planck assumed that the number of springs that were switched on at each frequency were what determined the distribution of the blackbody's energy across wavelengths.

The only way Planck could mathematically derive the known shape of the blackbody radiation spectrum was to assume that his conceptual springs could only absorb and emit packets of energy proportional to their oscillation frequency. He was, in essence, forced to assume that energy is stepped rather than continuous. This **quantization** of energy was an important indication that energy comes in discrete pieces and is not continuous.

THE PHOTOELECTRIC EFFECT

There is additional evidence for the quantization of energy. In 1905, Albert Einstein explained the **photoelectric effect**: the phenomenon where a metal plate emits electrons in the presence of certain wavelengths of light, irrespective of that light's intensity. He posited that light comes in "packets" of set amounts of energy, and that electrons could absorb only set amounts of energy. The electrons would be knocked off the metal plate only if the light packets contained the exact energy that the electrons could absorb—the packets of light each needed to have the right amount of energy. Having *more of them* would not knock off electrons.

[121] Kumar, *Quantum*, 23.

In other words, energy became *quantized* rather than continuous, as it had been before. Additionally, light could be shown to act as a particle, not only as a wave. Its ability to act as both a particle and a wave is referred to as **particle-wave duality**.

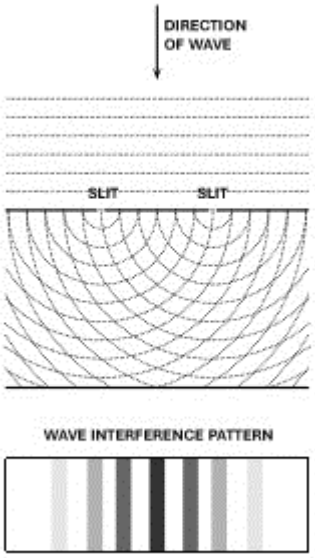
This concept of discrete quanta, which was in agreement with the math Planck used to solve the ultraviolet catastrophe, was fundamental to the development of quantum mechanics.

THE DOUBLE-SLIT EXPERIMENT

The quantization of light was not its only strange behaviour. In the early 1800s, physicist Thomas Young performed the first **double-slit experiment**. The experiment involves a beam of light passing through two slits in a sheet—hence the name "double-slit" experiment—in front of a wall (see **Figure 34**).

We would expect that if light behaves like a particle, it will form two bands as the "particles" of light pass through two slits. We would expect that if light behaves like a wave, the wave of light will split into two as it passes through the two slits, and then the two waves will form an interference pattern like ripples in a pond; on the wall, we would see *more* than two bands. Young's experimental results matched the latter case, proving that light behaves as a wave. Similar experiments can be performed with particles with mass whose results show that these particles can also behave as waves.

Figure 34
The double-slit experiment interference pattern



5.1.2 THE STANDARD MODEL

The experiments described above formed a portion of the basis for the now widely accepted Standard Model of particle physics. The Standard Model describes particle interactions, the behaviour of three of four fundamental forces, and other quantum phenomena.

I will begin this section by describing three of the more important ideas of quantum mechanics: Heisenberg's uncertainty principle, the Pauli exclusion principle, and fields. These three concepts are not exclusive to the Standard Model, but they are so essential to descriptions of the Standard Model that I have included them within this section.

HEISENBERG'S UNCERTAINTY PRINCIPLE

One of the most important ideas in quantum theory is the superposition of states. If a quantum system can be observed to be in states A or B, where each state is a set of

properties needed to describe the system at a given instant in time, then it can exist in a *combination* of states A *and* B, simultaneously. This combination of states is referred to as a **superposition**.

The problem arises when we actually observe the quantum system, because the actual act of observation affects the system itself. If we want to look at it with our eyes or equipment, we need to introduce a photon to **see** it—and introducing that photon will change the system. We cannot measure both the position and motion of a particle, just one or the other; so, we cannot measure the full state of the system. When we observe it, we get either A or B, but before we observe it, it is in the superimposed combination of states rather than simply having a probability of being A and a probability of being B.

The concurrent existence of a combination of two states goes against our common sense understanding of the world and introduces the idea of unresolvable uncertainty.

THE PAULI EXCLUSION PRINCIPLE

The Pauli exclusion principle states that fermions—a type of particle I will discuss in more detail later within this section—cannot occupy the same quantum state. Put more simply, it states that the smallest components of matter can only get so close to each other. Particles that do not have mass, like the photons that make up light, can get infinitely close.

FIELDS

Electromagnetic radiation can be thought of as a field. English physicist Michael Faraday, in the nineteenth century, performed various experiments investigating the behaviour of electricity and magnetism. Instead of describing the forces as occurring as if by magic at a distance, he described the forces he observed as having some value at every point: a **field** of points.[122]

Later in the twentieth century, another English physicist, Paul Dirac, worked out equations to describe the potential values a physical variable can take and the probability that the physical variable will take those values.[123] He then noticed that those same equations also worked to describe the behaviour of *fields* and not just particles. This was a huge leap in describing the behaviour of quantum mechanics: fields and particles describe the same thing.

[122] Rovelli, *Reality Is Not What It Seems*, 55–56.
[123] Rovelli, 123–24.

Faraday's electromagnetic field, for example, is another way of describing photons.

This duality extends to other particles. Every particle can be thought of as a small perturbation in its corresponding field.[124]

FUNDAMENTAL FORCES

There are four fundamental forces:

1. Electromagnetism
2. Gravity
3. Strong nuclear force
4. Weak nuclear force.

In 1864, Scottish physicist James Clerk Maxwell was able to demonstrate mathematically that both electricity and magnetism were different ways of looking at the same force, which was then called **electromagnetism**.[125] Light is an electromagnetic wave.

Gravity is the force that attracts particles with mass together. It is extraordinarily weak—think of how large the Earth is, and then consider that you can still jump into the air. Gravity is only strong when vast amounts of mass accumulate. However, despite its weakness, it is able to act over very large distances. Gravity is the only force out of the four fundamental forces that is not explained by quantum mechanics.

There are two nuclear forces: strong and weak. These act over tiny distances, or, in other words, on a nuclear scale, hence the name.

The **strong nuclear force** is, as its name implies, stronger; it holds together quarks, a type of subatomic particle that I will discuss later in this section. In 1973, physicists David Gross, David Politzer, and Frank Wilczek showed that the strength of the strong nuclear force has an unusual property. Instead of decreasing with distance, as we would intuitively expect given our macroscopic experiences with forces like gravity or magnetism, its strength increases with distance. Because of this, trying to separate quarks from each other requires such a high input of energy that separating them will create *more* quarks. Quarks, then, never exist individually.[126]

[124] Rovelli, 127.
[125] Kumar, *Quantum*, 133.
[126] Sean M. Carroll, *The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World* (Oxford: Oxford Paperbacks, 2012).

The **weak nuclear force** is unusual in a different way. It is involved in certain types of particle interactions, and allows the transformation of particles into other types of particles, such as in the conversion of protons into helium in the Sun. Its behaviour is much different than the other three fundamental forces because of this. The reason for this is related to the Higgs boson, which I will discuss later in this section.

Each of these forces, aside from gravity, arises from what is known in quantum mechanics as a symmetry. Symmetry is when one thing in a situation, such as a particle, can be swapped out for another, without affecting the behaviour of the situation. I will discuss symmetries in more detail in **Section 5.1.4**.

It is important to note now, however, that the weak nuclear force requires that a certain type of symmetry be broken—or, in other words, be hidden from our direct experience—in order for particles to have mass.

PARTICLES

There are three broad categories of accepted particles: fermions, bosons, and the Higgs boson. **Fermions** are the particles that make up matter and take up space, while **bosons** are the particles that carry forces between other particles and can be stacked on top of each other. [127] The **Higgs boson** is in a category all on its own.

FERMIONS

The category of fermion is further divided into two subcategories: **baryons**—particles that are made up of an odd number smaller particles called **quarks**—and **leptons**—all particles that are *not* made up of quarks. Atoms are made up of a combination of baryons and leptons. Both the proton and the neutron are baryons, and the electron is a type of lepton.

There are six types of quark, typically referred to as "flavours." They are:

1. Up
2. Down
3. Strange
4. Charm
5. Top
6. Bottom

Different combinations of quark flavours create different types of particles. Two up quarks and one down quark, for

[127] Carroll.

example, make up a proton, while two down quarks and one up quark make up a neutron.

Leptons are all matter particles that are not made out of quarks. Electrons, muons, and tau particles are leptons, and each of those leptons comes with an associated neutrino, also a lepton.

BOSONS

There are four main types of boson, three of which have been observed experimentally and one that remains hypothetical. The bosons each correspond to one of the fundamental forces:

1. Photon (experience electromagnetic interaction)
2. W and Z bosons (experience weak interaction)
3. Gluons (experience strong interaction)
4. Graviton (hypothetical; experience gravity)

There are also unstable bosons called **mesons** that are made up of equal numbers of quarks and anti-quarks. They are produced in some particle interactions but have a short lifespan and disappear almost immediately. I will discuss anti-quarks more in **Section 5.1.5**.

THE HIGGS BOSON

The Higgs boson is a special case. Confirmation of its existence in 2012 at the Large Hadron Collider in Switzerland was arguably the biggest discovery in experimental particle physics since the 1970s, when the rest of Standard Model had become so thoroughly examined that few surprises about it remained.[128]

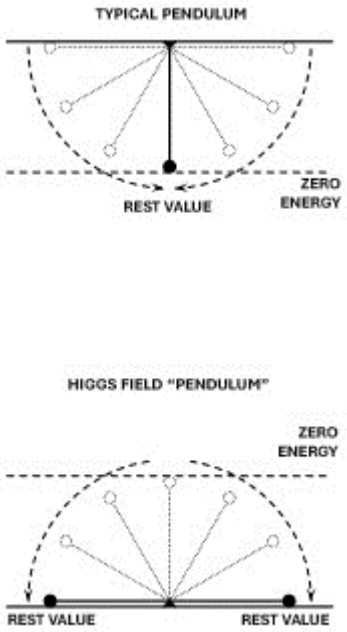
The Higgs boson was proposed in the 1960s, in part by Peter Higgs, the physicist for which it was named. There is a particular field—some quantity that has a value at every point in space—that pervades the entirety of the universe. It is referred to as the **Higgs field**. Other fields, like the gravitational field or the electromagnetic field, have a resting default "empty" state of zero, when they carry no energy.

The Higgs field, on the other hand, has a resting default state that is *not* zero; in other words, the state at which it has the least energy is when its value is nonzero. The Higgs field, then, is generally nonzero everywhere. American physicist Sean Carroll suggests that we imagine the

[128] Carroll.

Higgs field as a pendulum attached to the ground rather than the ceiling[129] (see **Figure 35**).

Figure 35
The behaviour of the Higgs field imagined as a pendulum. A typical pendulum's rest value is at zero energy, while a Higgs field conceptual pendulum's rest value is at a nonzero energy.



Call zero energy the point at which the pendulum is perpendicular to the surface it is attached to. A "normal" field and pendulum would have a rest state of zero, hanging straight down. The Higgs pendulum, on the other hand, would have a rest state of being on the floor. Raising the Higgs pendulum to the zero point would require an *input* of energy.

The **Higgs boson** is the particle generated by vibrations in the Higgs field. It is, technically, a force-carrying particle like the other bosons, although it behaves in a unique manner. Two particles can exert a Higgs force on each other via the exchange of a Higgs boson.

The most notable thing about the Higgs, though, is the resting nonzero value of the Higgs field. The Higgs field does not directly influence the behaviour of matter but is instead part of the mechanism by which the other particles' masses are generated. The field, because it has a nonzero value, acts as a medium for other particles and forces to interact in. Particles' masses are proportional to the strength of their interactions with the Higgs field.

As stated earlier, the weak nuclear force requires that a certain type of symmetry be broken in order for particles to have mass. The existence of the Higgs field provides this breakage. In Sean Carroll's pendulum metaphor, the Higgs field chooses to fall to either the left or the right.

5.1.3 MORE ABOUT PARTICLES

QUANTUM CHROMODYNAMICS

Quantum chromodynamics is a theory that was developed in the early 1970s by applying the gauge principle to the strong nuclear force, one of the four fundamental forces.

The "problem" with particle physics in the mid-1900s was the discovery of several particles, such as the muon and the kaon, which were not yet properly accounted for within a theoretical model. Experimental physicists' attempts to break up these particles into constituent part failed, and so for the time being they were thought to be elementary particles—in other works, not made up of smaller particles.

[129] Carroll, 139–42.

However, the development of the quark model independently by American physicists Murray Gell-Mann and George Zweig suggested that these particles were *not* elementary and were instead made up of different combinations of quarks. Korean-American physicist Moo-Young Han and Japanese-American physicist Yoichiro Nambu independently determined that giving the up, down, and strange quarks a property with three options would rectify some issues within the quark model. Gell-Mann named this property **colour**.

This "colour" is unrelated to the typical meaning of the word. It is analogous to electrical charge for interactions involving electromagnetism, but for the strong nuclear force. Similarly to how electric charge is mediated by the exchange of photons, colour would be exchanged between quarks with the hypothetical particles **gluons**. However, when three quarks of distinct colours— "red," "green," and "blue"—are added together, they add up to "white." Colour can then be a useful analogy when discussing baryons—such as protons and neutrons—which need to have one of each quark colour, or, add up to "white".

PREON MODELS

It is well-established within quantum mechanics that some particles are made of even smaller particles, like protons and neutrons being made of different combinations of quarks. If we apply this idea further, as several teams of physicists did in the 1970s and beyond, we can break up *those* sub-particles into yet smaller particles called **preons**.[130]

Preon models use two preons that make up quarks, electrons, and some other particles. The emergent properties produced by combinations of preons explains some features of the Standard Model that are otherwise unexplained, such as the fact that two characteristics of quarks—colour and charge—each have three options.

The issue with preon models is that it has not been determined what force would bind preons together; this has led to preon models being largely discarded.

ENTANGLEMENT

A hypothesis of quantum mechanics that has not been discarded, and has instead been met with experimental proof, is quantum entanglement.

[130] Lee Smolin, *The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next* (Boston: Houghton Mifflin, 2006), 167.

Imagine that we have a physical system composed of two particles. Each particle exists, as I described earlier, in a superposition of two states. Under certain circumstances, the two-particle system, too, can exist in its *own* superimposed state. Then, if we measure one particle and cause it to "decide" its state, the second particle will also "decide" its state. In other words, after measuring the first particle we will then also know the state of the second particle.[131]

If we separate those two entangled particles by any arbitrarily large distance, their behaviour will remain unchanged; measuring one will tell us the state of the other, making it appear to us that information from the distant particle has arrived to us instantaneously, faster than the speed of light.[132]

5.1.4 SYMMETRIES

A concept integral to the field of quantum mechanics is symmetry. Although "symmetry" is a word in common usage used to refer simply to purely geometrical symmetry, symmetry in quantum mechanics uses the term differently. The quantum mechanical version of symmetry begins with the gauge principle.

THE GAUGE PRINCIPLE

The gauge principle is an idea based in symmetry: it is the idea that certain operations one can perform on a system, such as switching out one type of particle for another, will not change how the system *behaves*, like how rotating a square ninety degrees does not change its behaviour, or how conducting an experiment a second time but three feet to the left will not change the outcome.

Symmetry can be **broken** in the sense that a symmetry can be hidden from our direct experience. It still exists in the underlying mechanics of the universe, but something picks a preferred "direction" for the symmetry. Imagine if nature only let us see the left side of a square, but the full unbroken square does exist.

The gauge principle appears in many of the major quantum theories, such as supersymmetry, the Georgi-Glashow Model, and quantum chromodynamics.

[131] Sten Odenwald, *Quantum Physics: The Complete Guide to Quantum Physics, Including Wave Functions, Heisenberg's Uncertainty Principle and Quantum Gravity*, Knowledge in a Nutshell (Arcturus Digital Limited, 2019), 146.

[132] Dariusz Kurzyk, "Introduction to Quantum Entanglement," *Theoretical and Applied Informatics* 24, no. 2 (January 1, 2012): 135, https://doi.org/10.2478/v10179-012-0010-7.

The difference between the observed phenomena—electromagnetism's long range versus the strong and weak nuclear forces' ranges—are because laws have a symmetry that is respected by only some of the features of the world, not all of them. The forces start out with infinite range, but symmetry can spontaneously break, which causes some forces to end up with finite range. The combination of spontaneous symmetry breakage with gauge theories was conceived of by François Englert and Robert Brout, as well as independently by Peter Higgs; it is known as the Higgs Phenomenon. The Higgs Boson is a consequence of spontaneous symmetry breaking.

Applying the gauge principle to quantum mechanics results in three of the four fundamental forces: electromagnetism, the strong nuclear force, and the weak nuclear force. Each of these forces is conveyed between particles by another type of particle: a **gauge boson**. For electromagnetism, it is the photon; for the strong nuclear force, it is the gluon; and for the weak nuclear force, it is the weak boson.

SUPERSYMMETRY

The theory of supersymmetry is an extension of the gauge principle. It is an attempt to unify particles and forces; in other words, unify fermions and bosons. It posits that you can replace fermions with bosons in an experiment without affecting the probabilities of the possible outcomes of the experiment. The pairs of particles that can replace each other are called **superpartners**, and supersymmetry posits that *every* particle has a corresponding superpartner.

All models of supersymmetry require a doubling of particles to create superpartners, which have never been experimentally observed. There has been no successful theory where *existing* particles have been made into superpartners of each other. It has been suggested that to explain the lack of observed superpartners, that supersymmetry can be spontaneously broken. The constants in the equations need to be tuned so that all the superpartners are too heavy for us to currently produce in particle accelerators.

A supersymmetric theory can't rely on a spacetime that changes in time; spacetime has to be constant. Note that this is precisely the opposite of what we know in the theory of relativity.

GEORGI-GLASHOW MODEL & SU (5)

The Georgi-Glashow Model is a theory of particle physics that again relies on the gauge principle. The simplest version of the Georgi-Glashow Model is referred to as SU (5).

SU (5) is a proposed symmetry that would unify quarks (governed by the strong nuclear force) with leptons (governed by the electroweak force), which would reduce the two types of particle into a single type of particle, and also a singular gauge field.[133]

The theory predicts that quarks can change into electrons and neutrinos in a process similar to radioactive decay, with a very small decay rate. This decay rate, however small, is still within experimental testability; however, it has not been experimentally observed.

5.1.5 WEIRD MATTER

Because quantum mechanics deals with the nature and behaviour of matter at the smallest scales, it also suggests the presence or provides explanations for unusual types of matter that we do not encounter on Earth.

ANTIMATTER

In the 1920s, British physicist Paul Dirac formulated a set of equations related to the behaviour of fermions. These equations implied that for every fermion, there is a corresponding antiparticle. A proton would have a corresponding antiproton, a neutrino would have a corresponding antineutrino, and so on. Each antiparticle was expected to have the same mass as its counterpart, but an opposite electric charge.

American physicist Carl Anderson, in 1932, used a cloud chamber to experimentally verify the existence of the positron, the antiparticle counterpart to the electron.[134] He observed the trails that particles passing through a chamber filled with gas and supersaturated water vapour; the supersaturation means that the water will condense to form droplets when provided with something to condense on. A charged particle passing through the cloud chamber will knock electrons off of the vapour in the chamber, resulting in the formation of ions. These ions provide the water vapour something to condense on, and the

[133] A gauge field is a field that mediates the interactions between particles. Perturbations within a gauge field are bosons.

[134] Carroll, *The Particle at the End of the Universe*.

condensing water vapour will draw out the trail of the passing charged particle.

Anderson observed trails of particles that travelled in both clockwise and counterclockwise arcs, implying the passage of both positively and negatively charged particles. These could be protons, which are positively charged, and electrons, which are negatively charged. However, he also noticed that the width of the particle trails differed, which would in turn imply the mass of the particles. The trails implied the existence of small particles, which could be electrons, that were instead positively charged. [135]

However, the material of our day-to-day lives is exclusively normal matter. Anderson had to go searching for antimatter. The question, then, is *why* is the universe full of normal matter, and apparently no, or very little, antimatter? Part of the explanation for the lack of antimatter is the vigorous reaction of antimatter with normal matter. When matter and antimatter meet, they annihilate each other and release a spectacular amount of energy.[136]

The question becomes: why does the universe have so much more normal matter than antimatter? At the Big Bang, matter particles and antimatter particles may have been produced in equal quantities. These particles would then mutually annihilate, giving off enormous amounts of energy in the form of photons. The extreme energy of these photons would then create new pairs of normal particles and antiparticles, which would then also annihilate. However, in the moments before annihilation, it is possible that *some* of the particles had sufficient time to interact with each other to produce different *types* of particles. Then, as the universe expanded and cooled, the photons being produced through particle-antiparticle interactions would no longer have the energy necessary to form new particle-antiparticle pairs. This could have resulted in a slight excess of normal particles over antiparticles, and eventually resulted in the abundance of normal matter in the universe we see today.[137]

[135] He ruled out the possibility that he was simply misinterpreting backwards particle trails by introducing a sheet of lead at one side of the cloud chamber to slow down particles coming from that direction, allowing the direction of the particles to be discerned.

[136] Gato-Rivera, *Antimatter*, 12.

[137] Gato-Rivera, 218.

DARK MATTER THEORIES

I described dark matter in Chapter 4.1.3. Some of the many theories intended to explain dark matter are based on particles, either proven or posited, in quantum mechanics.

Detecting dark matter is difficult because it does not interact through electromagnetism, which is the method by which we detect most celestial phenomena. It is also difficult because all the matter that we are familiar with *does* interact electromagnetically; if dark matter does not behave in a way with which we are familiar, then it is entirely possible that it is made up of a *new* type of matter.

Weakly-interacting matter particles (**WIMPs**) are a hypothetical candidate for dark matter. They have zero charge—charged particles interact via electromagnetism, or, in other words, with light, and we know dark matter does not do that. Additionally, WIMPs would not interact significantly via the strong nuclear force, because we can see from dark matter's diffuse distribution that it does not interact strongly with itself. They would interact gravitationally. As their name implies, they would interact via the weak nuclear force. Simulations predict that the abundance of WIMPs matches closely with the measured abundance of dark matter, and so they remain a decent candidate for dark matter.

Another hypothesized dark matter particle comes from the theory of quantum chromodynamics: the axion, named by American physicist Frank Anthony Wilczek after a washing detergent because it would be able to clean up issues regarding the behaviour of strong interactions.[138]

5.2 HIERARCHY AND THE OBSERVER

There are, fittingly, two ways that I see to interpret hierarchy through the lens of quantum mechanics.

A HIDDEN UNDERLYING REALITY

The first is to consider the hierarchy implied by quantum mechanics' description of particles being divided into smaller and smaller pieces. Each part is made up of smaller and more fundamental pieces. We can see this idea continuing in other quantum mechanical models

[138] Wolfgang Kapferer, *The Mystery of Dark Matter: In Search of the Invisible*, Astronomers' Universe (Berlin, Heidelberg: Springer Berlin Heidelberg, 2021), https://doi.org/10.1007/978-3-662-62202-5.

even when there is no direct evidence for that to be the case; atoms are made partially of protons which are made of quarks, and quarks are then, without experimental evidence, suggested to be made of preons.

This stacking of pieces of the universe at its most fundamental level is still vertically hierarchical, but instead of the structure of the cosmos being dictated by a higher power from the top down, the structure of the cosmos is ordered from the bottom up. The aggregate behaviour of the underlying grains that make up matter results in the emergent characteristics of the macroscopic world we can directly observe. Quantum mechanics reveals a hidden reality below the one that we experience.

Faraday had, early on, suggested that sunlight was a form of electromagnetic energy; however, because it could not be proven with math, his idea was not accepted at the time. Since math proofs are a method to prove that something is always true for a given set of circumstances, everywhere, they act as a demonstration that the physical laws of the cosmos are universal. Math was becoming the dictator of what could be considered "real," a theme which I will later discuss further in Chapter 6.

The notion of hidden underlying layers of reality appears in art. Before the early 1900s, painting in the West "relied exclusively on the external appearance of things."[139] Later, however, particularly with the rising popularity of Cubism, other artistic techniques were used. An example of this is a 1902 encyclopaedia that describes architecture not with plans and typical sections, but with perspectival cutaway drawings to display the interior (see **Figure 36**).

Figure 36
An architectural perspective drawing using a cutaway technique to display the interior, from a 1902 encyclopaedia

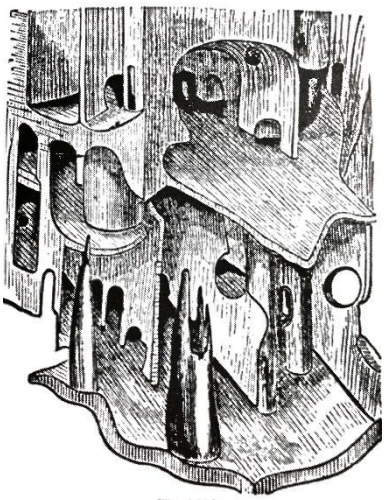


Fig. 2884.
HALLS AND GALLERIES OF THE CARPENTER ANT.

Despite this hierarchical interpretation of quantum mechanics reversing its order and prioritizing building blocks at the bottom of the hierarchy over a hierarchical structure imposed from the top down, it still retains an emphasis on and a desire for a vertically hierarchical structure.

We can see this in the language used to refer to concepts in quantum mechanics. People widely refer to the Higgs boson as the "God Particle," and I suspect that most people who have heard that term have no idea what the Higgs actually is, only that it is somehow important. Physicists, broadly speaking, do not refer to it as such—it is a pop cultural term that has more to do with public perception of

[139] Tony Robbin, *Shadows of Reality: The Fourth Dimension in Relativity, Cubism, and Modern Thought* (New Haven: Yale University Press, 2006), 39.

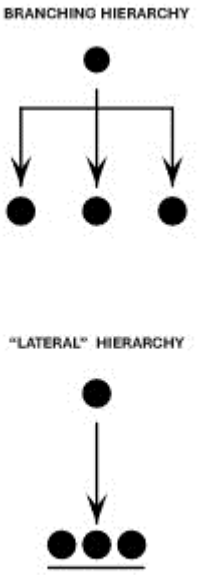
physics than the reality of physics. Whether the term "God Particle" is used metaphorically or in reference to religion, it still evokes a sense of a hierarchy.

The search in particle physics for the most fundamental unit of the universe is, in its own way, a search for the most important governing principle of the universe. I will explore this idea more in **Chapter 6** when I discuss the search for a unified theory of physics.

A HIERARCHY OF TWO

The second way that I see to interpret hierarchy through the lens of quantum mechanics is to examine instead the frequency of paired elements in quantum mechanics.

Figure 37
Diagram of hierarchical organization strategies



Quantum mechanics describes a world in which things often come in pairs. We see the pairing of particles in the fundamental forces with their accompanying carrier bosons, in supersymmetry where every particle has a hypothetical corresponding superpartner, and in certain particles like quarks never existing individually. This pairing together of elements is unlike what we see in the other hierarchical organizations I have described. Instead of a branching hierarchy—whether top-down or bottom-up—with one element being superior and subordinate to other elements, paired or grouped elements create a hierarchy in which elements can also be organized laterally and together (see **Figure 37**).

The location of the observer in quantum mechanics fits into this interpretation of hierarchy. When dealing with the behaviour of particles on a subatomic scale, the world is split into two parts: the system that is being studied, and the observer and measuring equipment.[140] I do not mean to imply that these two parts are wholly separate. Observation of the system of particles determines the state in which the particles are found. To measure a particle, you must perturb its system—perhaps with a photon so you can see it—which means that for it to have a non-probabilistic, definite state, interaction between the two halves of the world must occur.

This division of the world into two privileges the observer. If the act of observation is what decides reality, then the observer is more hierarchically important. However, one of the failings of quantum mechanics is the typical framing of the observer as external to the system being measured, rather than as a second *system* interacting with the first. American theoretical physicist Lee Smolin explains

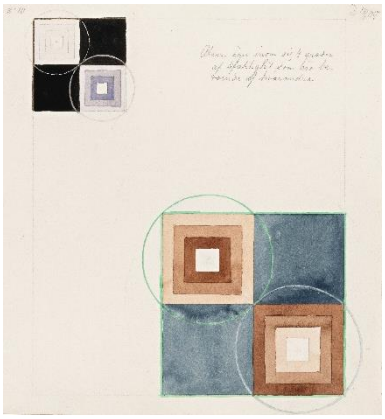
[140] Smolin, *Three Roads to Quantum Gravity*.

that "[w]hat you see as a measurement, [he] see[s] as two physical systems interacting with each other."[141] Either way, I see the pairing of a system of particles with an observer as an extension of the "hierarchy of twos" that I am proposing.

The Swedish artist Hilma af Klint took inspiration from the doubling of elements in particle physics. Her *Atom* series of drawings, in addition to being directly inspired from particle physics, was created to describe the spiritual planes af Klint believed in.[142] The series is twenty-two drawings; all of them feature a large and a small image, with the small version representing the atom on the "etheric" plane[143] and the large version representing the atom's energy state in the physical world. One such drawing can be found in **Figure 38**.

Her works use polarization between two ends of a spectrum as the basic organizational principle of the world, such as yellow versus blue for the masculine versus the feminine; she imagined unity between opposite poles. This demonstrates the tension between duality and unity that appears in particle physics.

Figure 38
Atom no. 10 (1917) by Hilma af Klint, showing two abstract interpretations of an atom.



5.3 FORCE AND MATTER

THE UNCERTAINTY OF MATTER

Quantum mechanics tells us that the behaviour of matter on a subatomic scale is vastly different from its behaviour at a macroscopic scale. The uncertainty principle suggests that the world is far from absolute and is instead a haze of probability, and that even the boundaries of matter that certainly feel solid to use are, in reality, uncertain.

These ideas show up in German painter Franz Marc's work, such as in his painting *Blue Horse with Rainbow* of 1914 (see **Figure 39**) which depicts the form of a horse merging with that of a rainbow, both combining with abstract shifting shapes that suggest an ongoing destruction of interior and exterior conditions. The overlapping of architectural elements could evoke uncertainty, as could less strictly defined edge conditions.

Figure 39
Blue Horse with Rainbow (1914) by Franz Marc. Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY. The abstract, shifting shapes suggest uncertainty.



[141] Smolin, *The Trouble with Physics*.
[142] Hilma af Klint, *Notes and Methods* (New York Chicago: University of Chicago Press, 2018).
[143] A term used by af Klint and others to refer to the part of the world that would allow connection between the physical body and the soul.

Figure 40
Composition no. 7 (1913) by Wassily Kandinsky. The painting uses overlapping, ambiguous shapes to suggest uncertainty.



Figure 41
Quantum Man (2006-07) by Julian Voss-Andreae. The statue appears either solid or transparent depending on the point of view.



Figure 42
Woman in the Triangles (ca. 1909) by František Kupka. Photo: Centre Pompidou, MNAM-CCI/Service de la documentation photographique du MNAM/Dist. GrandPalaisRmn. The shapes overlap like an x-ray image.



Russian painter Wassily Kandinsky attributed his art style becoming more abstract to the discovery in physics that atoms are not solid, saying, "The collapse of the atom was equated, in my soul, with the collapse of the whole world. [...] Everything became uncertain, precarious, and insubstantial."[144] He incorporated these ideas into his work by using overlapping, ambiguous shapes, such as in his piece *Composition no. 7* (see **Figure 40**).[145]

Several sculptures made by German artist Julian Voss-Andreae play with the visibility of forms. He layers flat sheets of steel in such a way that their shape is revealed when viewed from one direction and hidden from another, an effect which is intentionally reminiscent of the uncertainty of quantum mechanics. Voss-Andreae uses the interplay of volume with minimal material in his sculptures as "an apt metaphor for the ephemeral nature of the quantum object."[146] His statue *Quantum Man* (see **Figure 41**), as Voss-Andreae describes, uses the parallel sheets of steel to represent wavefronts of a particle behaving as a wave. He suggests that the sculpture can be interpreted as a metaphor for wave-particle duality in quantum mechanics. [147]

The principle of inherent uncertainty in quantum theory is reflected—in spirit, if not literally—in the unclear, overlapping boundaries of the shapes in Cubist art. For example, the painting *Woman in the Triangles* by Czech painter František Kupka ca. 1909 (see **Figure 42**) distinctly resembles the dark, overlapping shapes characteristic of an x-ray and the way that they reveal the otherwise unseen interior of the figure.[148]

EMANATION

The quantum mechanical description of particles, particularly of light, evokes the sense that force, matter, and energy emanate outwards from some point. Matter and antimatter collide and emanate energy from the point of their collision, light emanates outward from a blackbody, and so on.

[144] Wassily Kandinsky, "Reminiscences," in *Kandinsky 1901-1913*, trans. Peter Vergo (Berlin: Der Sturm, 1913), quoted in Gamwell and Tyson, *Exploring the Invisible*, 247–48.
[145] Gamwell and Tyson, 247.
[146] Julian Voss-Andreae, "Quantum Sculpture: Art Inspired by the Deeper Nature of Reality," *Leonardo: Journal of the International Society for the Arts, Sciences and Technology* 44, no. 1 (2011): 17.
[147] Julian Voss-Andreae, 17.
[148] Gamwell and Tyson, *Exploring the Invisible*.

Street Light, painted in 1909 by Italian artist Giacomo Balla (see **Figure 43**), is a clear example of artistic interest in visualizing motion. It portrays the light emitted by an electric street light as a dynamic series of V-shaped, coloured marks that spread out radially from the lamp itself; the colour and density of marks vary according to distance. The painting visually suggests a spray of pieces of light as they are emitted from their source. Balla himself noted the influence of science on his work, saying, "This painting… is also scientific because I tried to represent light by separating it into the colours that compose it."[149]

Architecturally, think of the difference between light that is emitted directionally versus light that radiates out in all directions from its source. The first might feel more limited and focused, while the second might feel like it is interacting more broadly with the entire space.

UNINTUITIVE FORCE BEHAVIOUR

Quantum mechanics, which deals with three of the four fundamental forces of the universe, could have unintuitive implications for the nature of force itself. In daily life, we mostly think about gravity and light because they are the forces that we can physically sense on a macroscopic scale. The two subtler and more easily disregarded fundamental forces, strong nuclear force and weak nuclear force, behave much differently than either gravity or light.

We are, for example, used to force strength decreasing with distance. Gravity follows this rule, as does intensity of light. Strong nuclear force, however, behaves in the opposite manner—its strength *increases* with distance. An architectural interpretation of this property of strong nuclear force could create novel spatial qualities; it would suggest an inversion of the expected architectural response to forces.

For example, the architectural depiction of force of the **Vlooyberg Tower** in Belgium (see **Figure 44**) and BIG's **Marsk Tower** in Denmark (see **Figure 45**) both depart from the sense of a downward pull of gravity, but in different ways. The Vlooyberg Tower appears to ignore gravity entirely. The Marsk Tower, however, inverts gravity rather than disregarding it. The structure is larger towards the *top*, whereas usually, due to the increased need for structural support towards the bottom layers of buildings, we

Figure 43
Street Light (1909) by Giacomo Balla © Giacomo Balla / SIAE, Rome / CARCC Ottawa 2024. Photo: Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY. The light is a series of individual V-shaped marks rather than a continuous gradient.

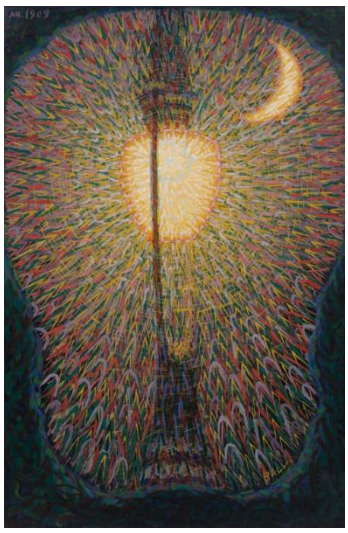


Figure 44
Sketch of elevation of Vlooyberg Tower showing its apparent disregard for the effects of gravity.

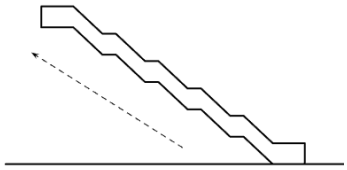
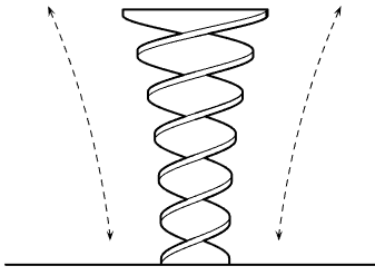


Figure 45
Sketch of elevation of Marsk Tower showing its structure enlarging towards the top.



[149] Giacomo Balla, "Letter to Alfred H. Barr Jr.," May 24, 1954, quoted in Gamwell and Tyson, 233.

intuitively expect more of a building's mass to be towards the bottom.

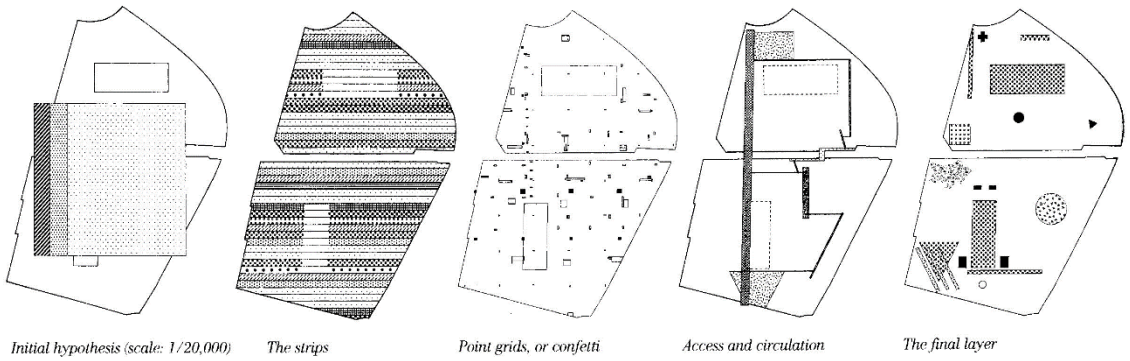
5.4 SPACE, TIME, AND MOTION

OBJECTS IN SPACE

Quantum mechanics ignores gravity, and thus also disregards the warping of space that we see in the theory of relativity. It is as if particle interactions instead occur within an abstract, disconnected, unchanging backdrop. I interpret this architecturally as looking at the objects in space rather than directly at the formation of space itself.

For an example of what I mean by this, we can look at OMA's unbuilt plan for Parc de la Villette (see **Figure 46**). It uses four organizational strategies, all overlaid on top of each other: strips, point grids or confetti, access and circulation, and a final layer of other features. The strips form a sort of unidirectional background grid. The other layers sit over this background grid in a somewhat disconnected way, as if they are objects floating in the space laid out by the grid rather than part of the shape of the grid itself.

Figure 46
OMA's plan design for Parc de la Villette (1982), divided into its constituent layers. The strips form a unidirectional background grid, while other layers appear to be made up of objects floating in the space laid out by the grid.



6 A UNIFIED THEORY OF PHYSICS

6.1 CONTEXT

Quantum gravity is the unresolved theoretical crossing-over point between relativity and quantum mechanics. Relativity deals with only gravity, but there are three other fundamental forces: strong nuclear force, weak nuclear force, and electromagnetism. Quantum mechanics deals with these three forces, but not gravity. Creating a theory that accounts for both gravity and the other three fundamental forces would form a quantum theory of gravity.

Quantum gravity would also need to resolve other aspects of quantum mechanics and relativity. Quantum mechanics is background dependent and assumes that there is a fixed background against which all things happen; in other words, it does not manage the view of an observer in the same way that the theory of relativity does. Quantum mechanics also has not resolved gravity, as no gravitons have been detected, while general relativity deals primarily with gravity.

That the theory of quantum gravity remains unresolved means that its ideas have been unable to ripple through broader culture in the same way that discoveries during the Scientific Revolution, the theory of relativity, and quantum theory have; this does not mean, however, that the ideas produced in the search for quantum gravity have not proliferated whatsoever. String theory particularly has found a home in art and pop culture.

The two most promising versions of quantum theories of gravity arose in the 1980s: loop quantum gravity and string theory. There are, of course, many other avenues of exploration regarding a quantum theory of gravity, such as twistor theory, but I will focus on the aforementioned pair as these are currently considered the most viable.

Loop quantum gravity and string theory have some commonalities, the main one being that they deal with a "physical scale on which the nature of space and time is very different from that which we observe"[150] and that this scale is, with currently available technologies, impossible

[150] Smolin, *Three Roads to Quantum Gravity*, 24.

to measure. This scale is possibly at somewhere around twenty orders of magnitude smaller than even an atomic nucleus and is known as the Planck scale.

These two theories also agree on one fundamental characteristic of space itself: that it, like the energy of photons and particles, is quantized rather than continuous.

It is also possible that the two previous theories, since they are based on existing incomplete theories, are themselves inherently inadequate. It is possible that unifying physics will require an unconnected approach.

6.1.1 FROM RELATIVITY, LOOP QUANTUM GRAVITY

Loop quantum gravity was initially developed in the late 1980s by working forward from the principles of relativity and expanding them to include quantum phenomena. It is successful in expanding on the possible behaviour of space but fails to produce any of the particles or fundamental forces.

LOOPS

The theory started from the physicist Abhay Ashtekar's work in 1986 reformulating Einstein's theory of general relativity into similar mathematical terms as quantum theory. Smolin and fellow American physicist Ted Jacobson then found that the mathematical solution to these new equations is a series of closed lines, typically referred to as **loops**.[151] Smolin and Italian theoretical physicist Carlo Rovelli showed that these solutions also implied that both volume and area are quantizable—there is a smallest possible unit of area and a smallest possible unit of volume.

SPIN NETWORKS

The loops were found, mathematically, to be organized into a graph, with nodes each surrounded by a "packet" of volume and connected to other nodes by links. Rovelli and Smolin later found that a type of diagram conceived of by Roger Penrose, the spin network, worked as a way to describe these graphs. The spin network represents the quantum states of the gravitational field. An encircled collection of the nodes of the spin networks produces a given **volume** of three-dimensional space, and the "line" segments that cross the edge of the encircled area produce the **surface area** of that volume.

[151] Rovelli, *Reality Is Not What It Seems*, 159.

SPIN FOAM

When time passes for the spin network, it can experience changes in which of its vertices are connected. The four-dimensional—the four dimensions being the three spatial dimensions plus time—structure that results is described as **spin foam** due to the foamlike appearance of the visualizations of this process.

THE HOLOGRAPHIC PRINCIPLE

"**Information**" in the context of physics is a measure of the number of possible alternative outcomes. It does not count a possible outcome if it's correlated with an existing outcome, since the latter tells us the first. Additionally, it's important *how* things like atoms are *combined*, not just what the atoms are. Because the way atoms are arranged correlates with how *other* atoms are arranged, a set of atoms can contain *information* about another set of atoms. Another example is that the light we see carries information about whatever it's reflected off of or refracted through.

It is this specific definition of information that is used when investigating what occurs at the boundary of a black hole. Analysis of black hole thermodynamics suggests that there is a limit to the amount of information that a region of space can contain. This limit, called the **Bekenstein bound**, is proportional to the area of the region's boundary. That there *is* a limit suggests that the area of the region's boundary must be discrete and not continuous: a continuous area could contain an infinite amount of information.[152]

The **holographic principle**[153] is the idea that observation of a physical system is functionally equivalent to observing a screen that transmits information about that physical system.[154] That screen can receive and transmit electromagnetic radiation about the physical system but cannot otherwise interact with us.

The idea of the holographic principle, or the world as equivalent to a screen, distinctly contrasts with architecture, which relies on tangible experience of the physical world.

[152] Smolin, *Three Roads to Quantum Gravity*, 296.

[153] The holographic principle is found in theories other than loop quantum gravity, including in string theory. However, I include it only within the loop quantum gravity exhibit hall because the idea of a screen dovetails nicely with the theory's suggestion that the *border* of a region of space is correlated with area and volume.

[154] Smolin, *Three Roads to Quantum Gravity*.

BLACK HOLE EVIDENCE

A challenge with both loop quantum gravity and string theory is the difficulty in obtaining experimental evidence. However, the extreme conditions around black holes provides possible avenues for observational tests.

A team of French and American researchers proposed in 2011 that the evaporation of black holes could produce observational data proving or disproving loop quantum gravity.[155] The entropy[156] of a black hole is proportional to the area of its "surface," but the equations formulating loop quantum gravity suggest that the quantization of volume and area will leave telltale markers in the evaporation spectrum of the black hole.[157]

Black holes provide another possible avenue for obtaining evidence for or against loop quantum gravity. When black holes collide and merge, they produce waves in spacetime known as gravitational waves. These gravitational waves have already been detected and are known to agree with the theory of general relativity.[158] Analysis of the harmonics and overtones of these waves may provide hints about the behaviour of gravity at very small scales.[159]

6.1.2 FROM QUANTUM THEORY, STRING THEORY

String theory was initially formulated in 1960s from ideas and methods used in quantum theory. It was developed to describe the behaviour of the elementary particles and forces.

String theory successfully produces the particles and forces of the Standard Model, and also produces the graviton. However, there remains no widely agreed upon version of string theory, and no version of it successfully models the warping of space-time we see in relativity.

EARLY STRING THEORIES

In 1968, Italian physicist Gabriele Veneziano noticed a pattern in the probabilities of two strongly-interacting

[155] A. Barrau et al., "Probing Loop Quantum Gravity with Evaporating Black Holes," *Physical Review Letters* 107, no. 25 (December 16, 2011): 251301, https://doi.org/10.1103/PhysRevLett.107.251301.

[156] Entropy is the amount of disorder in a system. It is highly related to the amount of information in the system.

[157] A black hole evaporates over time by giving off electromagnetic radiation. Charting the amount of radiation against wavelength gives a black hole's evaporation spectrum.

[158] "What Are Gravitational Waves?," LIGO Lab | Caltech, accessed June 28, 2024, https://www.ligo.caltech.edu/page/what-are-gw.

[159] Dongjun Li et al., "Perturbations of Spinning Black Holes beyond General Relativity: Modified Teukolsky Equation," *Physical Review X* 13, no. 2 (May 25, 2023): 021029, https://doi.org/10.1103/PhysRevX.13.021029.

particles—in other words, particles that are made of quarks—to scatter from each other at different angles. The formula that described this can be interpreted as the particles not being points, but being instead one-dimensional **vibrating strings** that stretch when they gain energy and contract when they lose energy. The different modes of vibration of these strings then produces what we observe as particles, creating their properties of mass, charge, and so on.[160]

Earlier versions of string theory could be formulated to be consistent with both special relativity and quantum mechanics given a set of specific conditions: [161]

1. There are 25 spatial dimensions.
2. Tachyons, a hypothetical particle that moves faster than light, exist.
3. Massless particles that cannot be brought to rest exist.

There is no experimental evidence for extra spatial dimensions or tachyons. Additionally, there are no strongly interacting particles with no mass, and the theory did not yet produce quarks; these two facts combined posed problems for string theory when it was initially developed as an investigation into strong interactions.

SUPERSYMMETRIC STRING THEORIES

In 1970, French physicist Pierre Ramond adjusted the string theory equations to produce fermions. To accomplish this, he added a new symmetry, which would connect bosons with fermions—this is the same type of symmetry that we find in quantum mechanics' supersymmetry, and so Ramond's theory is referred to as **supersymmetric string theory**. His adjustments removed the need for tachyons entirely and reduced the number of required spatial dimensions to 9.

Physicists John Schwarz and Michael Green completed calculations in 1984 that showed that in a ten-dimensional supersymmetric string theory, there are no anomalies. This made string more plausible, and it became far more popular as a field to focus on. However, there were *five* consistent supersymmetric string theories in ten dimensions, not a single theory.

There are dualities between supersymmetric string theories. In this context, "duality" refers to the idea that there are two different ways to describe the same phenomena,

[160] This interpretation was developed independently by Yoichiro Nambu, Holger Nielsen, and Leonard Susskind.

[161] Smolin, *The Trouble with Physics*.

or that one type of phenomena is similar to another and can approximate it. Supersymmetric string theories have two dualities: T-duality and S-duality. The dualities suggest that different versions of supersymmetric string theory either describe the same phenomena, or that one version of the theory approximates another.

T-duality—where the "T" stands for "topological"— is a duality between two string theories that wrap around a circular dimension. If one of the curled-up dimensions of string theory is a circle, a string can wrap around that circle n number of times, where n is the **winding number**. A second number describes the string's mode of vibration. In T-duality, the radius of the circular dimension in one string theory is the inverse of the radius of the *other* string theory's circle. In this case the winding state of the first string theory behaves the same as the levels of vibration of the second string theory.

S-duality—where the "S" stands for "strong-weak"—is a duality involving the probability of strings breaking apart or joining together.

If we denote the constant g to refer to the probability that a string will break or join, called the **string coupling constant**, we can say that a small g produces weak interactions and a large g produces strong interactions.

If one version of string theory has a string coupling constant of g, and a second string theory has a string coupling constant of $\frac{1}{g}$, then the two theories behave identically assuming S-duality. This is because there are more strings in the two theories than there are "supposed" to be due to the presence of *emergent* strings. An emergent string arises out of the collective motion of large numbers of fundamental strings. The more the fundamental strings interact, the less emergent strings interact, and vice versa. This means you can view the *emergent* strings as fundamental, and vice versa. That is where the duality arises.

The question that the existence of these two dualities brings up is of whether they are different versions of some underlying single theory, or truly different theories.

M-THEORY

In 1995, American physicist Edward Witten proposed that there exists a unified superstring theory, which he later referred to as **M-Theory**, and that it had certain characteristics. These characteristics involved dualities, as described earlier.

M-theory was developed further by American physicist Joseph Polchinski in 1995. He showed that for the dualities between the five superstring theories to work out consistently, in addition to strings there need to also be higher-dimensional dynamic *surfaces*. He called these **D-branes**, which are now often referred to as, simply, branes.[162]

One of the issues with string theory is that there is not a single accepted *formulation* of the theory. M-theory is hypothesized to exist, but has never been formulated.

BRANES

Branes were used to mathematically stabilize the higher dimensions. The higher-dimensional geometry can vary, which results in different versions of string theory. This geometry, if unconstrained, can also vary over time. To disallow this variation over time, we would need a version of string theory where everything happened in discrete steps, so that it would not be possible to flow smoothly between string theories.

Polchinski posited that branes were the discrete objects since in his model branes are wrapped around surfaces in extra dimensions and therefore come in discrete units. If branes are discrete, then the electric and magnetic flux they produce are *also* discrete. [163]

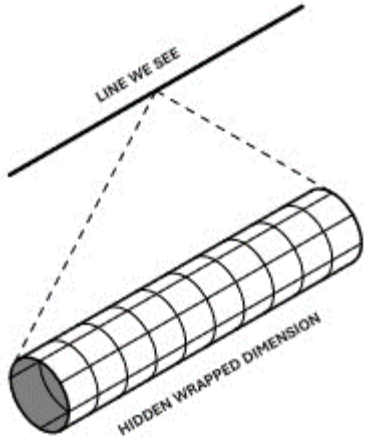
HIGHER DIMENSIONS

The higher dimensions required by string theory have never been observed, so for string theory to be true, they must somehow be hidden to us. They may, as suggested might be possible in 1926 by Swedish mathematician Oskar Klein, be curled up such that at the scale at which we exist a two-dimensional surface may appear as a one-dimensional line (see **Figure 47**).[164]

Supersymmetry string theory curls them up so that they are too small to be perceived, as seen in T-duality. However, the dimensions can be curled up in many ways, and because we have not observed them, we do not know which way might be correct, if any.

Curling up the dimensions in different ways produces different amounts of symmetry. The question is if there exists a way to curl up the extra dimensions in a way that

Figure 47
A two-dimensional surface curled up so that it appears to be a one-dimensional line at larger scales



[162] Smolin, 284.
[163] Smolin, 321.
[164] Stefan Kowalczyk et al., “Constraints on Large Extra Dimensions,” 2003, 3.

would produce the Standard Model of quantum mechanics.

PARTICLES AND FORCES

String theory's biggest success is the prediction of the particles and forces we see in quantum mechanics. It even produces the graviton, the hypothesized boson for gravitational force. The elementary particles arise from different modes of vibration of strings.

The relationship of bosons to strings is simple. The ends of an open string could be thought of as paired charged particles, like a negatively charged electron and its positively charged positron. The vibrating portion of the string in between the two charged particles is then the photon that carries the electrical force between them.

Gravitons are produced only by closed loop strings, so if there are only *open* strings, they are not produced. Closed strings *must* be included in string theory, though, because collisions between particles and antiparticles have been observed and produce photons; this is, in string theory, two ends of a string joining together.

All string theories predict the existence of particles that we have not observed. String theory also predicts extra forces that come along with the extra dimensions. There is no observed evidence for these extra forces either.

DARK MATTER

String theory's prediction of extra particles beyond the Standard Model provides potential explanations for the composition of dark matter. Many versions of string theory predict the existence of a particle called an **axion**, for instance.[165] However, these formulations of string theory also typically disagree with the widely accepted model of the universe's behaviour. While it is possible that there exists a hypothetical version of string theory that posits a type of particle that would explain dark matter, there remains no evidence to suggest that this is the case.

[165] Smolin, *The Trouble with Physics*, 391.

6.2 HIERARCHY AND THE OBSERVER

6.2.1 THE MATHEMATICAL DESCRIPTION

I believe that the biggest barrier to communicating the ideas of both loop quantum gravity and string theory is that they are primarily based in mathematics and not on experimental evidence gleaned from the material world. It is difficult to uncover the implications of a unified theory of physics because the mathematical process to arrive at the theories is so difficult for non-specialists, myself included, to follow. Conversely, while quantum mechanics and the theory of relativity also have complex underlying math, both use thought experiments that can be used as less “scientific” ways of explaining the theories without needing to be able to follow the details of their mathematical underpinnings.

Quantum mechanics and relativity, too, have been proven time and time again through real, observable physical evidence, while a unified theory of physics of any variety remains devoid of proof. This seems to me to make the equations of relativity and quantum mechanics secondary to witnessed physical reality, whereas the equations of loop quantum gravity and string theory remain mathematical tricks that, while intriguing and potentially accurate, are not as tangible as thought experiments or observable physical behaviours.

Compare, for example, the use of math in solving the ultraviolet catastrophe to the use of math to find the loop solution of loop quantum gravity. The math used in the former situation was to correct the mathematical model to conform to reality, and the equations used to do so then implied the new information of light existing as discrete pieces. On the other hand, the loop solution of loop quantum gravity was arrived at through a series of complex mathematical moves: the reworking of the existing equations of general relativity into a form more similar to the equations of quantum mechanics, the solution to these new equations being a loop. No *new* experimental evidence was needed to take these steps, neither in loop quantum gravity nor in string theory. Smolin, when discussing the rise of string theory, says, "No more reliance on experiment to check our theories. That was the stuff of Galileo. Mathematics now sufficed to explore the laws of nature. We had entered the period of postmodern

physics."[166] The focus on mathematics inserts a block between the theory and our experienced reality.

I would like to note that what little art based on string theory that I was able to find uses mathematical symbols and equations more extensively than the art I found that took relativity or quantum mechanics as inspiration. I believe that this is related to, in addition to the relative recency of the theory, the dependence on math that is needed for the explanations.

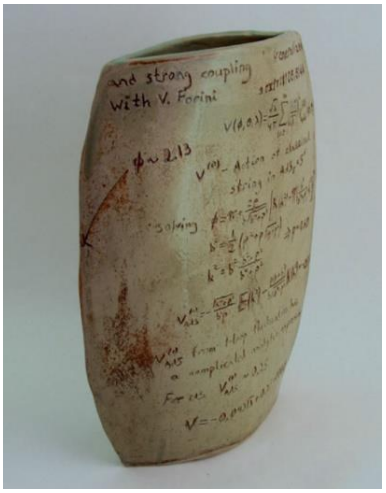
English sculptor Grenville Davey was the artist-in-residence for the Isaac Newton Institute for Mathematical Sciences while it was running its 2012 program *Mathematics and Applications of Branes in String and M-Theory*.[167] Some of the sculptures he made during this time are adorned in burned-in mathematical equations based on the work of David Berman, the organizer of the program and a theoretical physicist (see **Figure 48**).[168]

Figure 48
M-theory multiple in oak (2012) by Grenville Davey. The sculpture is covered in mathematical equations relating to string theory.



Potter and theoretical physicist Nadav Drukker made a series of ceramic objects inspired by different aspects of string theory, many of which are covered in mathematical formulae. His sculpture *Cusp-1* is fairly simple in shape and relies more heavily on the addition of writing to its surfaces to refer to string theory (see **Figure 49**). The cross-section of the ceramic piece is a Wilson loop of a specific shape: two arcs meeting at two points. The equations on each side of the sculpture depict different mathematical aspects of the specific theory he was interpreting.

Figure 49
Cusp-1 (2011) by Nadav Drukker. The ceramic piece is covered in mathematical equations relating to string theory.



Theoretical physics has become so mathematically niche that artists seem to be resorting to direct use of symbols and literal depiction of mathematical models over pure abstract expression. This is not to say that artists and sculptors taking inspiration from earlier theories did not *also* use written math or the shape of graphs, just that it seems to be more common in the relatively little art based on string theory. I suspect that this focus on math is likely related to the fact that both loop quantum gravity and string theory are still unproven and in the theoretical stage.

[166] Smolin, 116–17.
[167] "Grenville Davey," Isaac Newton Institute, March 22, 2021, https://www.newton.ac.uk/about/art-artefacts/grenville-davey/.
[168] "String Theory, Duality and Art: How the Higgs Boson and Turner Prize Collide," Plus Maths, accessed May 11, 2024, https://plus.maths.org/content/string-theory-duality-and-art-how-higgs-boson-and-turner-prize-collide.

6.2.2 THE IMPORTANCE OF THE OBSERVER

In quantum theory, as described earlier, the act of observation changes what we observe a quantum state to be. When we are trying to combine quantum theory—where the observer is outside the system—with relativity, the trouble arises because the observer—us—is *inside* the system. A possible solution to this problem was proposed by American physicist Hugh Everett in his Ph.D. thesis in 1957, a method known as the "relative state interpretation."[169] The relative state interpretation allows, given a question expressed appropriately in the language of quantum theory, the deduction of the *probabilities* of the different answers even when the instruments, or the observers, are inside the quantum system being measured.[170]

Other physicists, such as Smolin, Chris Isham, Jeremy Butterfield, Louis Crane, and Carlo Rovelli, have more recently supported making context dependence a "central feature of the mathematical formulation of quantum cosmology."[171] In other words, they support the idea that the place of the observer is integral to our understanding of the universe. In Smolin's words, the universe has "many different mathematical descriptions, each corresponding to what a different observer can see when they look around them. Each is incomplete because no observer can see the whole universe. Each observer, for example, excludes themselves from the world they describe. But when two observers ask the same question, they must agree."[172]

This line of thinking continues the long journey of shifting the place of the observer throughout history along with scientific discoveries: from being at the centre, to being offset from the centre, to being at a relative "centre," to emphasizing the position of the observer as very consciously inside the universe. While we have always placed ourselves as an observer inside the universe, the difficulty in measuring quantum phenomena draws the importance of our position as the observer more explicitly to the forefront of our understanding of the universe.

[169] Smolin, *Three Roads to Quantum Gravity*, 76.
[170] Smolin, 76.
[171] Smolin, 46.
[172] Smolin, 48.

6.3 FORCE AND MATTER

6.3.1 SPACE AS A MATERIAL (LOOP QUANTUM GRAVITY)

In trying to unify relativity with quantum theory, we see differences in the possible texture of the universe. Relativity describes the fabric of spacetime as smooth and—as evidenced by the words we use to describe spacetime—like fabric. On the other hand, quantum theory describes the particles of the universe as discrete, individual *quanta*, where matter is made of irreducible building blocks and forces are transferred by irreducible carriers. And quantum gravity, at least in the two incarnations of it on which I have focused, turns space itself into discrete quanta. Loop quantum gravity and string theory, despite their vastly different approaches, agree on one important thing: that space is not continuous and that there exists a smallest, irreducible unit of space.

Because loop quantum gravity in its current formulation does not deal with matter whatsoever and deals only with space, it is as if the void of space is the material of the universe. The idea of space as a material, of course, is not accurate. As Smolin puts it in his book *Three Roads to Quantum Gravity,* "it is simply absurd to speak of a universe with nothing in it. That is as absurd as a sentence with no words."[173] However, while loop quantum gravity succeeds in describing the possible nature of space, it makes no strides towards explaining matter. The loops of loop quantum gravity, I would argue, are material-like in the way a non-quantized view of space is not. Imagining a "piece" of space evokes a much different sensation than a continuum of space.

[173] Smolin, 25.

These two ways of envisioning space have different possible implications for architecture. Let us compare architecture that uses reasonably similar types of geometry: Theo van Doesburg's *Construction in Space-Time II* (see **Figure 50**) and Piet Blom's *Kubuswongingen*, or cube houses (see **Figure 51**). Both use primarily orthogonal planes, and both designs look like a series of cubes or rectangular prisms attached together.

However, *Construction in Space-Time II*, like much of Doesburg's work, is composed of a series of intersecting and overlapping planes that create the impression of a space divided in such a way that it is implied to be continuous. On the other hand, Blom's cube houses' repetition of an intersecting implied cubic form create the impression of a series of discrete spaces placed next to each other. Although both use a superficially similar type of geometry, the difference in how the geometry is organized suggests that either parts of a continuous space are divided, or that space itself is a building block, almost a material on its own.

Figure 50
Construction in Space-Time II (1924) by Theo van Doesburg. The overlapping planes create the impression that a continuous space is being divided.



Figure 51
Kubuswongingen (1984) by Piet Blom. Photo: Alexander Migl. License: CC BY-SA 4.0. The repeating forms imply that space is discrete.



6.3.2 DUALITY (STRING THEORY)

String theory's idea of duality—the concept that two separate theories are different descriptions of the same underlying behaviour—can be examined architecturally. Grenville Davey's work during his time as the artist-in -residence for the Isaac Newton Institute for Mathematical Sciences provides an example of duality in art. He was explicitly inspired by T-duality and symmetry in string theory.

Many of his sculptures come as paired objects. For example, one of the pieces Davey made during his time at the Isaac Newton Institute was several pairs of bowl-like objects made of various materials (see **Figure 52** for one example). The objects are double-curved, with the curvature of the bowl shape switching directions towards the centre to create a raised dome. Berman noted these sculptures' depiction of duality was expressed clearly by the fact that once you see one side of the sculpture, you can infer the shape of the other.[174]

Figure 52
A pair of sculptures made by Grenville Davey in 2012. The double-curvature of the sculptures appears differently from each side. Seeing one side implies the shape of the other.



[174] "String Theory, Duality and Art."

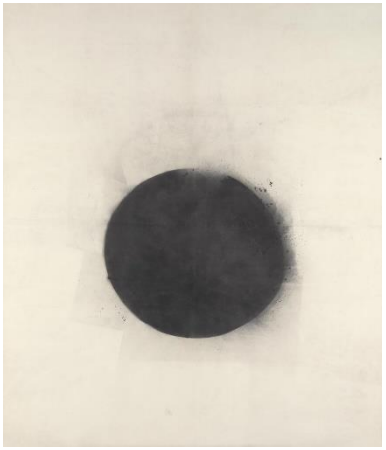
6.4 SPACE, TIME, AND MOTION

6.4.1 THE LEAST EVENT (LOOP QUANTUM GRAVITY)

Newtonian physics almost disregards time; when we describe something in Newtonian physics, we assume that we are looking at an object—its position, mass, and so forth—at a particular instant of time. It is taken for granted that the object exists. Classical science's assumption that the world is made up of objects, however, is an illusion, albeit often a useful one. [175]

In modern physics, objects are only snapshots of ongoing processes. As described by Smolin, "...there are not really two categories of things in the world: objects and processes. There are only relatively fast processes and relatively slow processes... [D]o not think of an event as a change happening to an otherwise static object."[176] The conception of the universe is moving to, it seems, one that is predominantly about relationships between elements, not one that is primarily described as objects in reference to a background coordinate system.

Figure 53
Full Stop (1961) by John Latham. © John Latham Estate, courtesy Lisson Gallery, London. Photo: Tate. The painting shows Latham's "least event" motif.



Loop quantum gravity suggests the possibility that there is actually a smallest possible unit of time, like we believe from quantum theory that there is a smallest unit of matter. This would make space *and time* not smooth and continuous; there would be the smallest possible *event* that could happen, that would be indivisible.

This was an idea expressed by the British artist John Latham. While Latham was interested in physics, much of his art was produced before loop quantum gravity was formulated. However, a recurring motif in his work succinctly and effectively evokes the idea of a smallest event: he used a single burst of spray paint to represent what he called the "least event" on a canvas.[177] This motif can be seen in his 1961 piece *Full Stop* (see **Figure 53**).

[175] Smolin, *Three Roads to Quantum Gravity*, 52.
[176] Smolin, 51.
[177] "John Latham: Time Base and the Universe | MoMA," The Museum of Modern Art, accessed May 17, 2024, https://www.moma.org/calendar/exhibitions/4867.

6.4.2 HIGHER, COMPACTED DIMENSIONS (STRING THEORY)

The higher dimensions of string theory differ slightly from the fourth dimension of relativity, which was either simply time or, in some art as discussed in **Chapter 4**, a fourth spatial dimension. String theory's higher dimensions are more explicitly invisible or even completely inaccessible to us.

This could be expressed architecturally as "missing" elements. For example, certain sets of Grenville Davey's sculptures come instead in threes, such as the circular, wall-mounted works shown in **Figure 54**. These come as sets of three to imply two matched pairs with one component missing, evoking both the idea of symmetry and of dimensions that cannot be observed.[178]

Figure 54
A triptych made by Grenville Davey in 2012. The set of three implies that there are two pairs and that one half of a pair is missing.



[178] "String Theory, Duality and Art."

7 DESIGN EXPLORATION

7.1 INTRODUCTION

The purpose of the design portion of this thesis is explore examples of how architectural language can be used to communicate ideas about the perceived structure of the universe.

7.1.1 PROGRAM CHOICE

For the program, I chose a science museum. I believe that this is appropriate for a few reasons. Firstly, our view of cosmology has shifted from being predominantly religious to predominantly scientific. Several of the buildings I looked at in the historical context chapters were churches, so perhaps science buildings are today's rough equivalent, although they may not have the symbolic strength that churches hold in our culture.

Additionally, a science museum's program provides the opportunity to not explore only the architectural metaphor that can be used in the broader gestures of the building, but also in the specific ideas in physics architecturally in the design of the individual exhibit spaces. Each exhibit area can use architectural analogy to convey, metaphorically, the content of its exhibits.

7.1.2 SCOPE

For this thesis, I am only designing the architectural exhibit spaces and not exhibit material as designing the material itself would massively increase the scale of the project. Exhibit material would be displayed on counters where available, hanging on the wall, or built on the floor flush to the wall.

7.1.3 SITE SELECTION

The site I have chosen is on the north side of Saint Mary's University campus in Halifax, Nova Scotia, at the intersection of Inglis Street and Tower Road (see **Figure 55** and **Figure 56**).

This location was chosen due to a number of factors. Halifax is a major city, but it is without much in the way of existing science museums. There is the Natural History

Museum, which focuses on ecology and geology, and the Discovery Centre, aimed at children's entertainment; there is no existing science museum or centre that explores modern physics or related topics.

Halifax is also home to multiple institutions for higher education: Saint Mary's University, as mentioned, as well as Mount Saint Vincent University, King's College, and Dalhousie University. I selected Saint Mary's University campus because of its strong physics program and because of its location in the Halifax downtown.

7.1.4 EXISTING CONDITIONS

The site consists of a wide, flat, open area that is partly lawn (see **Figure 57**) and partly a parking lot (see **Figure 58**), surrounded by a number of academic buildings. Both Saint Mary's University library and its science building are nearby; these are connected to the site via a small plaza (see **Figure 59**). There is an existing bus stop on the north side of the site (see **Figure 60**).

Two schools are close to the site: Inglis Street Elementary School to the northwest and Halifax Grammar school—a high school—to the east.

Figure 55
Map of Halifax showing the location of Saint Mary's University and other science-related buildings

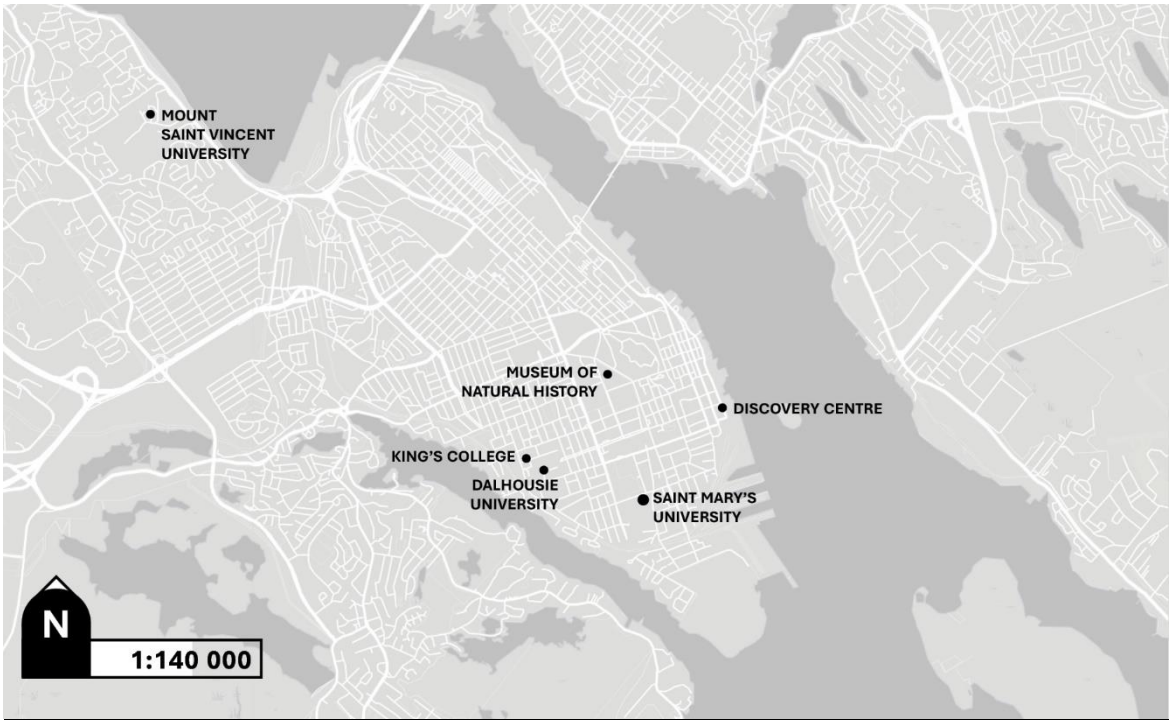


Figure 56
Site map of existing conditions at the north side of Saint Mary's University campus




WELLINGTON STREET
TOWER ROAD
INGLIS STREET
FIG. 58
LANGUAGE CENTRE
TOWER ROAD
HALIFAX
GRAMMAR SCHOOL
DAUPHINEE CENTRE

Figure 57
Photo of the lawn taken from the plaza facing east



Figure 58
Photo of the parking lot taken from the northeast corner of the parking lot, facing west



Figure 59
Photo of the plaza in front of the Science Building, Atrium Building, and Burke Building, facing south



Figure 60
Photo of the north side of the site, including the bus stop



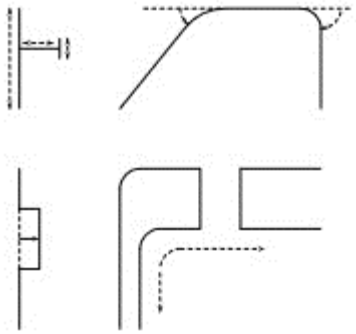
7.2 OVERALL DESIGN

7.2.1 GEOMETRY

GENERAL LANGUAGE

The typical geometry used in the design of the museum is shown in **Figure 61**. The elements in the building follow straight lines that are typically orthogonal with each other, but in some areas follow some set angles in the building; these angles are taken from the observed lines of motion through the site. Elements like walls and the edges of pathways and floors are sometimes rounded at intersections, depending on the sense of movement that the specific space is meant to evoke. The edges of walls or railings are occasionally inflected to create inset, built-in benches.

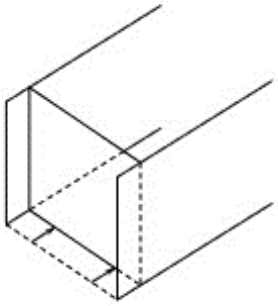
Figure 61
Plan sketches of examples of typical geometry



WALL JOIN CONDITION

Two parallel walls connected by a wall spanning between them will typically extend beyond that spanning wall, as seen in **Figure 62**. This use of geometry is designed to call to attention the surface of the wall spanning between them, whether that wall is flat concrete or a window to the exterior. In the cases of walls at the end of the broad gestures of the building shape, it is particularly intended to imply the continuation of the walls in the direction of that gestural motion.

Figure 62
Axonometric sketch of common wall join condition



ROOF OVERHANG

The continuation of the broad gestures of the building is also suggested by the shape of the roof overhangs (see **Figure 63**). The walls, as they reach the ends of the strips of the building, curve upwards to extend the shape of the roof in the same direction as the movement of the building. The shape serves to finish off the gesture of the building while also elongating the strips rather than ending them bluntly.

Figure 63
Axonometric sketch of roof overhang geometry

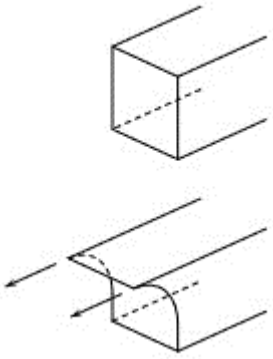
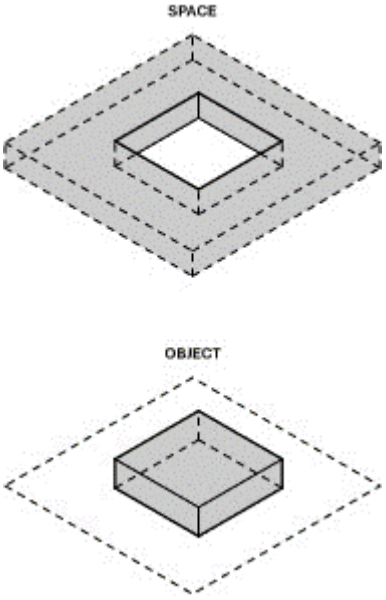


Figure 64
Axonometric sketch showing architectural difference between space (or void) and object



OBJECTS VERSUS SPACE

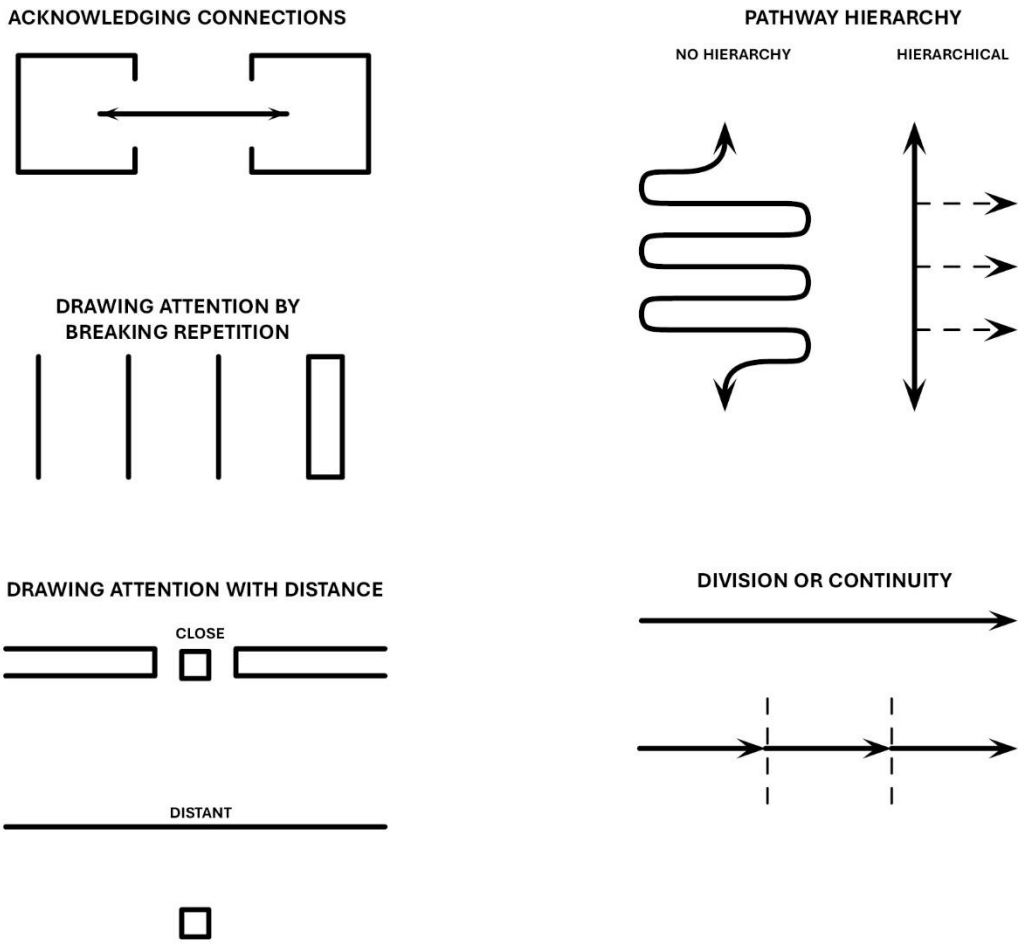
I use a specific spatial strategy to examine the difference between quantum mechanics and the theory of relativity. Relativity deals with space, and quantum mechanics deals with things *within* space. I use the strategy depicted in **Figure 64** to both distinguish between objects and space, and also to highlight that quantum mechanics and relativity are almost inverses of each other. "Space," in the theory of relativity exhibit hall, is suggested by the use of enclosing shapes. "Objects," in the quantum mechanics exhibit hall, are suggested by the visual and physical inverse of the enclosing shapes—standalone architectural elements.

MAJOR ARCHITECTURAL STRATEGIES

A visual glossary of the major architectural strategies used in the design of the museum can be found in **Figure 65**. The strategies are as follows:

1. **Acknowledging connections** between exhibit material by placing window openings between two otherwise unconnected areas.
2. **Drawing attention by breaking repetition** to call out a particular element as unusual.
3. **Drawing attention with distance** to call out a particular element as unusual. This can be accomplished by either "framing" elements with small gaps or by placing elements sufficiently far from other elements that their isolation becomes notable.
4. **Pathway hierarchy** can either be used or avoided.
5. **Division or continuity** of the possible pathways can be used in conjunction with pathway hierarchy.

Figure 65
A glossary of the major architectural strategies used in the museum.



7.2.2 MATERIALITY

Figure 66
Brick colours, separated by concrete

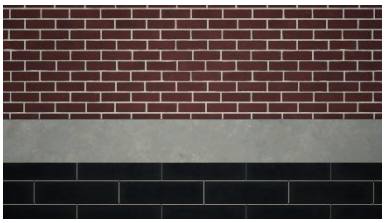
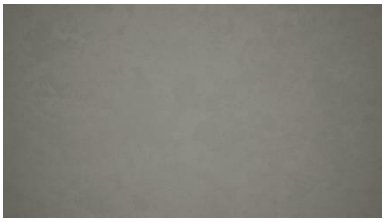


Figure 67
Terrazzo colours



Figure 68
Smooth lime plaster



I want the materials suggest a connection to the physical world around us. To do this, I chose to primarily use materials that feel grounded and tactile.

I chose to use the same material—and geometry—palette throughout the entire building, not only to give a sense of cohesion but also to suggest with architectural metaphor that all of the theories of physics present within the museum are different ways of looking at the same source.

I use two types of **brick**: a medium brown standard-sized brick, and a larger, darker brick (see **Figure 66**). The majority of both the interior and exterior of the building is clad in the typical lighter brick. For the sections of the building that are two storeys, the lighter brick is used above and the darker brick below to emphasize that the upper storey is raised up compared to the one-storey sections of the building. **Concrete** is used as a contrasting material, both in terms of texture—as it is smoother than brick—and in colour. Despite these differences, concrete maintains an immediate, tactile quality.

Two colours of **terrazzo** are used in the floors, again a light and a dark colour (see **Figure 67**). Changes in the floor colour delineate thresholds between sections of the exhibit halls.

The ceilings use various textures of **lime plaster** (see **Figure 68**). In each area, a smooth texture is combined with some other texture; I will describe the relevant secondary textures when I discuss each space in more detail.

7.2.3 ORGANIZATION & LAYOUT

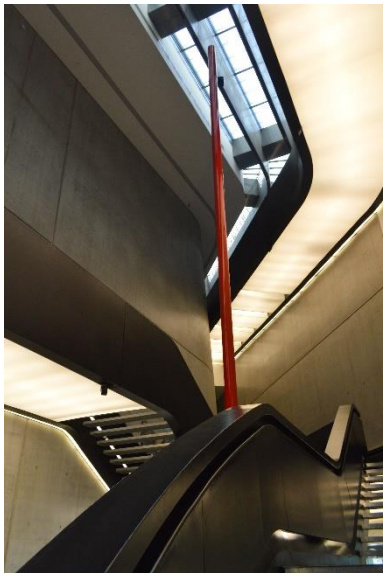
The main consideration for the design is that of its underlying order: the way in which the broad components of the building relate must reflect the changes in worldview according to developments in science over the past century. The modern scientific theories that I am focussing on are, like with geocentrism and heliocentrism, related to the **place of the observer**. In geocentrism, the observer is at the centre; in heliocentrism, the observer is offset from the centre; and in modern science, there **is no inherent centre** – a centre only exists insofar as we choose one as a reference point.

It is my belief that the role of the observer in the scientific theories I am considering is also more **active** than in either the geocentric or heliocentric models. In both of these older models, the observer occupies a fixed location on a celestial body. However, in special relativity, the observer must be moving at great speed in relation to another so-called "stationary" observer. Quantum theory has its uncertainty principle, wherein the very act of observation affects the outcome.

This suggests to me that there has been a shift in treating space like objects to treating it more as a series of processes. To this end, the guiding principle for the design of the building is that it should be organized following multiple strong lines of movement rather than as the more typical "chunks" of discrete locations. This serves to both decentre the visitors' point of view and give a sense of movement.

This organizational strategy can be seen to great effect in the MAXXI National Museum of 21st Century Art in Rome, Italy, designed by Zaha Hadid Architects. The building is made up of a series of long strokes that follow the lines of movement through the site (see **Figure 69**).

Figure 69
MAXXI National Museum of 21st Century Art, Rome. Photo by Francisco Anzola. License: CC BY 2.0. The lines of movement of the building are strongly visible.



To begin designing the museum, I first overlaid a series of possible movements through the existing site (see **Figure 70**). I then took these lines of movement and simplified them to create several broad gestures, the number and size of which corresponded to the number and relative size of each of the exhibit halls I wanted to include (see **Figure 71**).

The exhibit halls I included were:

1. The theory of relativity
2. Quantum mechanics
3. Loop quantum gravity
4. String theory

Loop quantum gravity flows out of the theory of relativity and string theory flows out of quantum mechanics. Because loop quantum gravity and string theory are both approaches to a unified theory of physics, I wanted the broad gestures of those two exhibit halls to fit together into a larger, implied gesture.

Roughly, I organized the museum with the theory of relativity exhibit hall to the north, the quantum mechanics exhibit hall to the southwest, and the loop quantum gravity and string theory exhibit halls to the southeast. A central

path, shown by the dashed line in **Figure 71**, acts as the division between the different approaches to physics.

The overall plans, sections, and elevations describing the museum are shown on the following pages (see to **Figure 84**). More detailed descriptions of each individual space comprise the remaining sections in this chapter.

Figure 70
Plan of lines of movement on the site

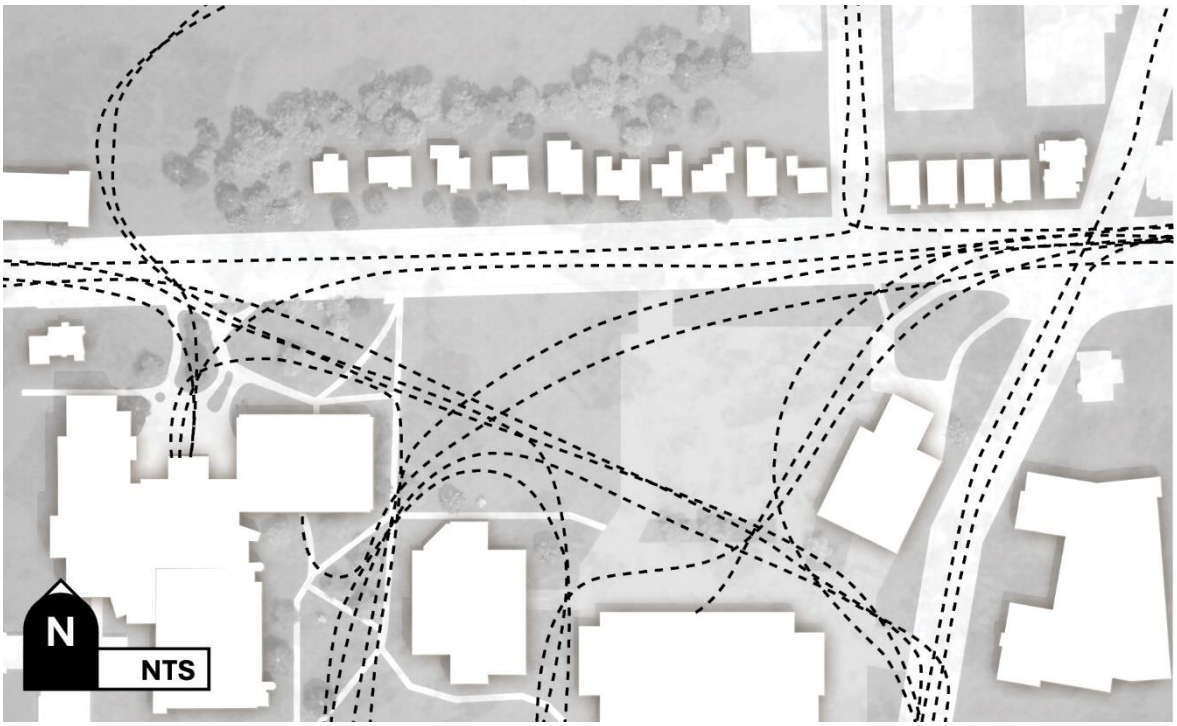


Figure 71
Parti sketch of site plan

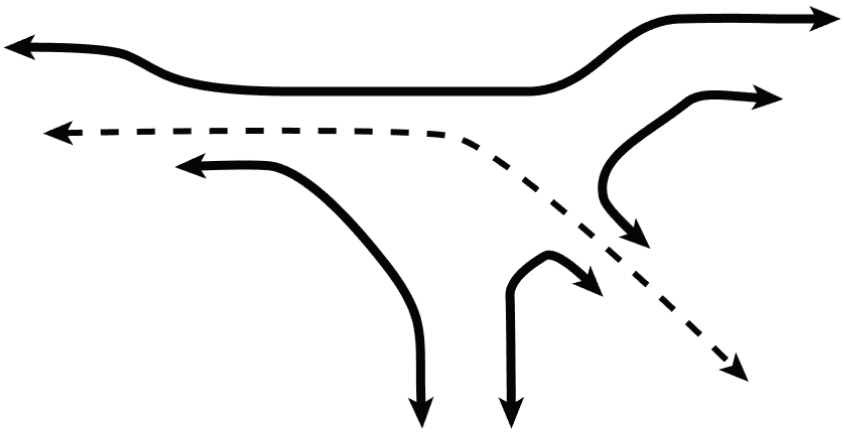
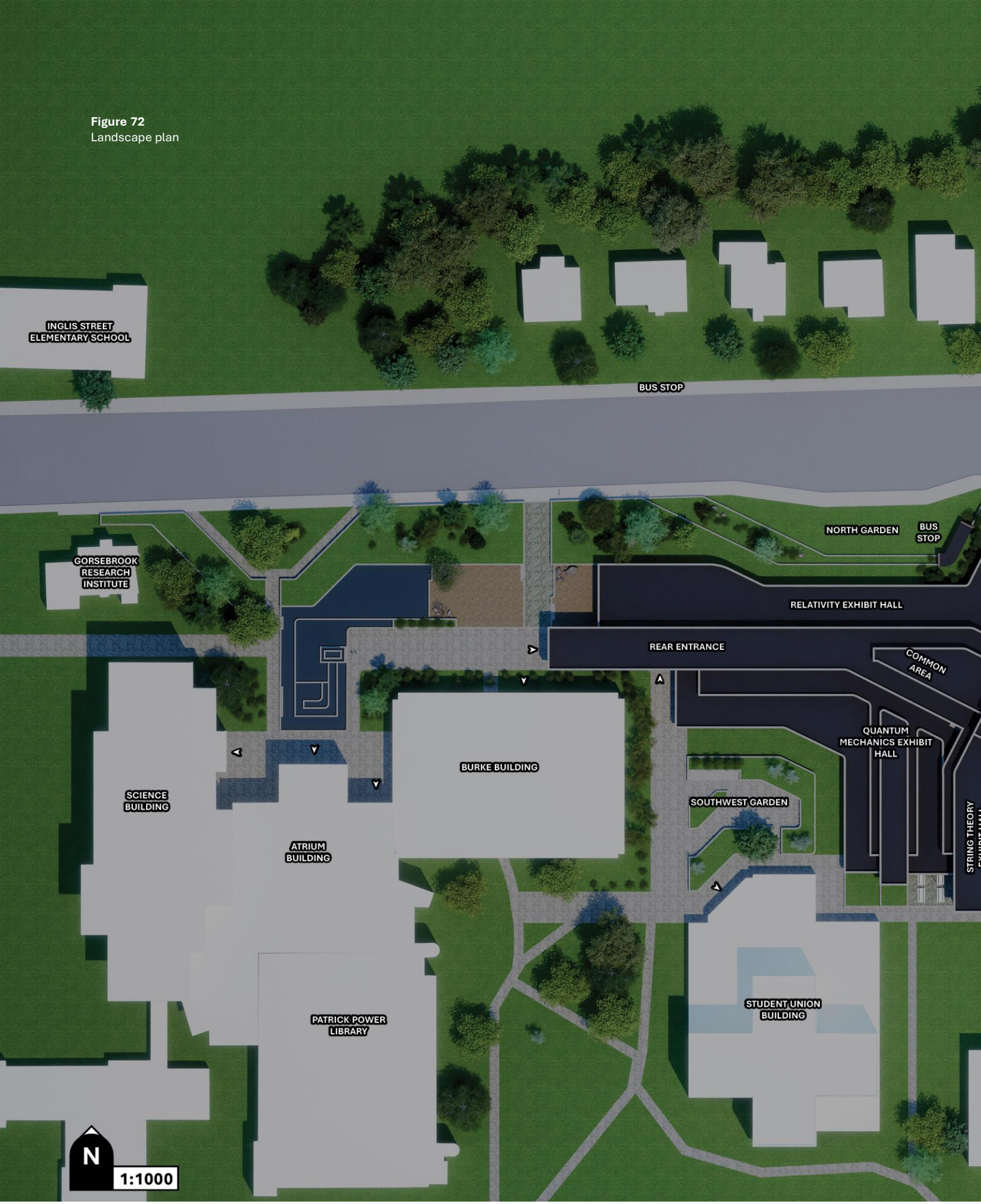


Figure 72
Landscape plan




WELLINGTON STREET
TOWER ROAD
INGLIS STREET
EAST GARDEN
LOOP QUANTUM GRAVITY EXHIBIT HALL
MAIN ENTRANCE
LANGUAGE CENTRE
TOWER ROAD
SOUTHEAST GARDEN
HALIFAX GRAMMAR SCHOOL
DAUPHINEE CENTRE

Figure 73
First floor plan



Figure 74
First floor reflected ceiling plan



Figure 75
Second floor plan



Figure 76
Second floor reflected ceiling plan



Figure 78
North elevation



1:1000

Figure 77
Southeast elevation



1:1000

Figure 79
South elevation



1:1000



Figure 80
West elevation



Figure 81
Section through main entrance, southwest to northeast



1:200

Figure 82
Section through main entrance, northwest to southeast



1:200

Figure 83
Section through quantum mechanics and theory of relativity exhibit halls, north to south



1:200

Figure 84
Section through quantum mechanics and string theory exhibit halls, west to east



1:200

7.3 LANDSCAPE

7.3.1 OVERALL

LAYOUT AND ORGANIZATION

See **Figure 72**.

There are five areas of landscaping: the north garden, the east garden, the southwest garden, and the west garden. While they follow a similar architectural language, each of these has its own type of organization. Broadly speaking, however, the landscaping in each garden follows the same gestural movements as the building itself.

GEOMETRY

The landscape is primarily composed of raised beds at multiple heights, following the same type of geometry as used in the building: long, sweeping shapes with straight edges sometimes inflected inwards by orthogonal cut-outs. The duplication of the building's geometry within the landscaping gives the sense that the gestures of the building continue beyond the building itself.

7.3.2 PARKING LOT

The majority of the new parking lot is parallel to the elevation of the museum's main entrance. The south portion of the new parking lot is parallel to the southern part of the building. The parking lot's curve thus follows the broad shape of the building; like the curves in the landscaping, this serves to emphasize the overall gestural movement of the museum.

The eastern edge of the new parking lot has been moved farther away from the Arthur L. Irving Entrepreneurship Centre entrance to allow for a more pleasant, less cramped entrance.

Figure 85
Key plan showing location of parking lot

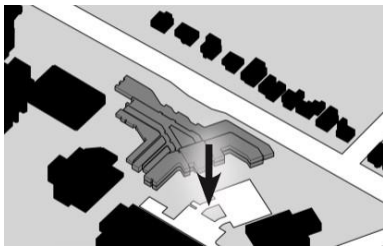


Figure 86
Plan showing parking lot



Figure 87
View of parking lot and main façade



Figure 88
View of parking lot, facing north



7.3.3 NORTH GARDEN

The north garden is located near, and can be viewed from inside, the theory of relativity exhibit hall. As such, the style of the north garden is based on concepts from the theory of relativity. The geometry of its landscape beds, therefore, is smooth and continuous. The landscape beds are particularly long to emphasize size and scale.

The plantings here are organized to evoke gravity. They are nestled into curved points in the north wall of the building and smaller plants group around larger plants as if gravitationally pulled towards the larger mass.

The existing bus shelter has been removed and replaced with a new bus shelter tucked into the curve created by the exterior wall at the intersection of the exhibit spaces for special relativity and general relativity. The bus shelter and its surrounding planting, as well as a new bus turnout pushed into the sidewalk, serve to provide a sense of gravitational pull towards the mass of the building.

The new bus shelter faces the direction of bus arrival for the convenience of people waiting there.

Figure 89
Key plan showing location of north garden

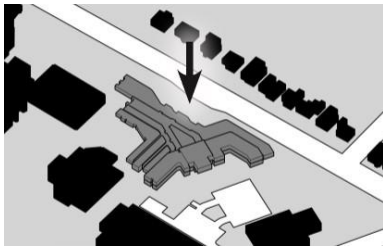


Figure 90
Plan showing north garden

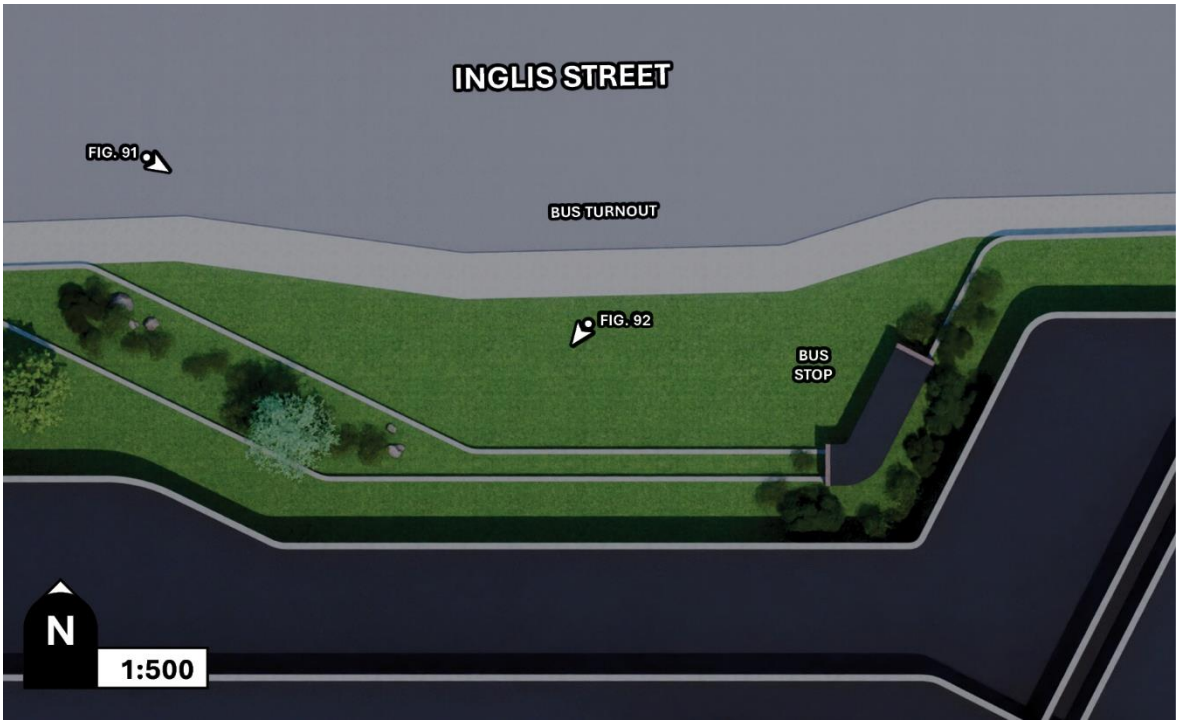


Figure 91
View of north garden



Figure 92
View of north garden



7.3.4 EAST GARDEN

The landscape beds and pathways of the east garden resume the gesture of the building to suggest continuity of form. Raised beds and plantings partially shelter the main entrance from the traffic of the main road, particularly the intersection.

The pathways provide multiple points of access between the main roads and the building to account for the multiple directions in which people may approach the site. One of the pathways opens into a larger, more open paved rest area that is sheltered from both the main road and the parking lot by raised landscape beds.

Figure 93
Key plan showing location of east garden

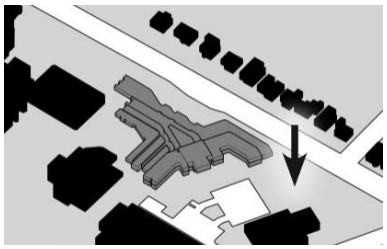


Figure 94
Plan showing east garden

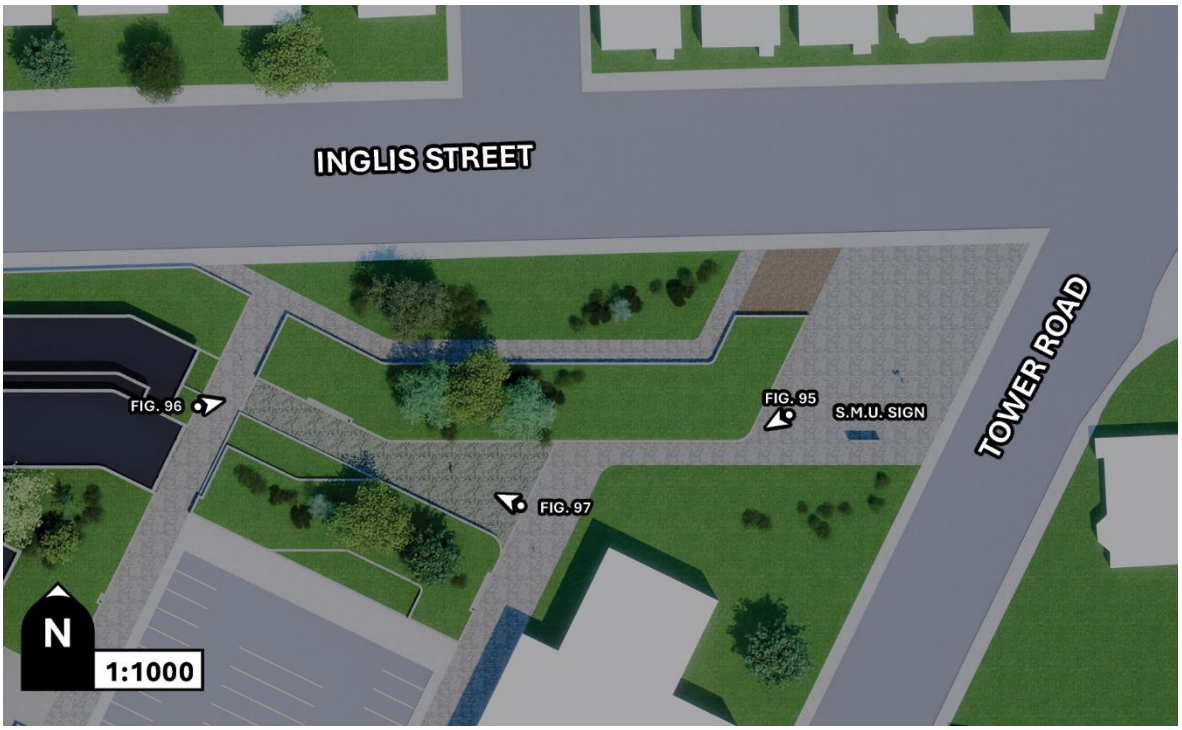


Figure 95
View of east garden



Figure 96
View of east garden



Figure 97
View of east garden



7.3.5 SOUTHEAST GARDEN

The southeast garden is located near the exhibit halls for quantum mechanics and string theory. As such, the southeast garden's landscape beds are broken up into smaller, discontinuous pieces. Two landscape beds to the west of the southeast garden simply extend the shape of the building to imply a continuation of the building's gesture in the same manner as the roof overhangs.

The landscape beds to the east of the southeast garden, in front of the main face of the museum, are more complex. A landscape bed follows the shape of the building. This, and another set of landscape beds, encloses a partially sheltered walkway and unpaved rest areas.

This second set of landscape beds is detached from the larger landscape bed near the building to evoke the idea of division and separation of parts. The shape of this set of beds references the shape of one of the exhibit spaces within the quantum mechanics exhibit hall—antimatter—the shape of which I will elaborate upon in the description of that exhibit space. Referencing the architectural language of part of the quantum mechanics exhibit hall is intended to both hint to visitors what they will see upon entering the museum, and to suggest that features within the quantum mechanics exhibit hall are doubled.

Figure 98
Key plan showing location of southeast garden

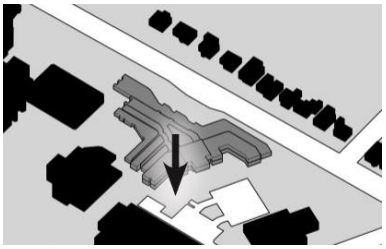


Figure 99
Plan showing southeast garden

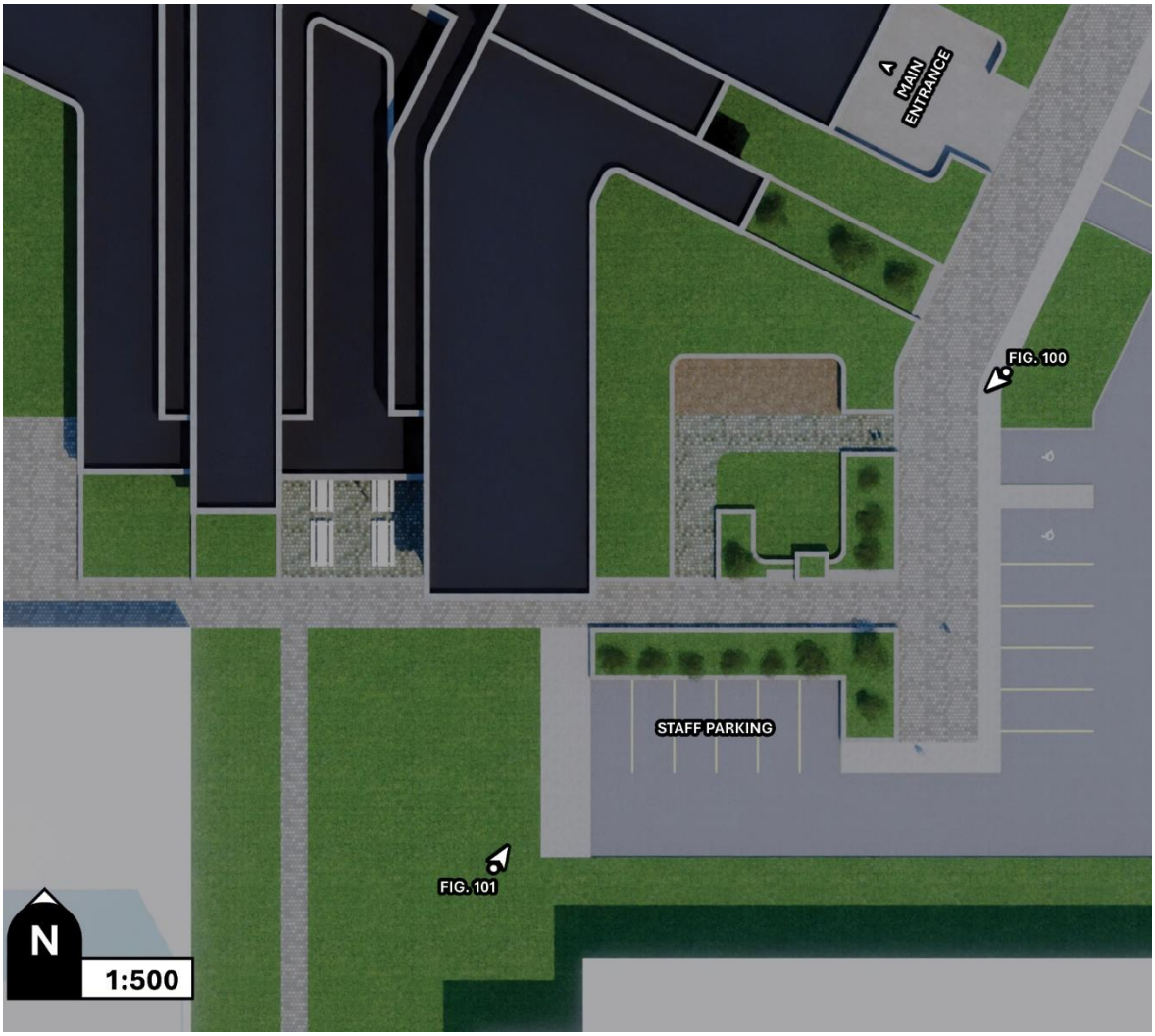


Figure 100
View of southeast garden



Figure 101
View of southeast garden



7.3.6 SOUTHWEST GARDEN

Like the southeast garden, the southwest garden is adjacent to the quantum mechanics exhibit hall. I intend this garden to emphasize the artistic interpretation of quantum mechanics as *objects in space* over space itself.

As such, the raised landscape beds in this garden are, rather than being directly adjacent to the building, detached and independent from the main mass of the building. The broken-up façade accentuates the sense of discontinuity.

To imply hierarchical structure, the plantings are highly organized both by size and placement. Variation in the scale of the plants is organized by ratio—one large plant next to three small plants, for example.

Figure 102
Key plan showing location of southwest garden

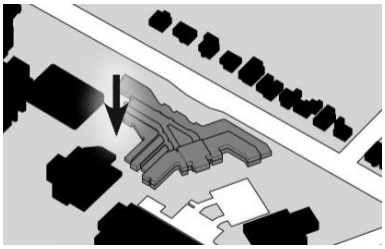


Figure 103
Plan showing southwest garden



Figure 104
View of southwest garden



Figure 105
View of southwest garden



Figure 106
View of southwest garden facing towards rear entrance



7.3.7 WEST GARDEN

Like the other gardens, the shapes of the landscape beds continue the gestures of the building. The beds here, however, wrap around the main feature of this garden: a fountain.

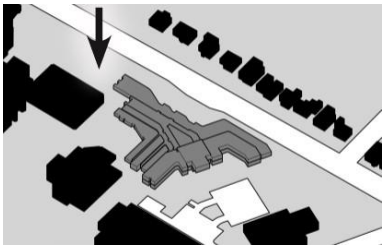
The fountain here is intended to create a sense of a mysterious point of interest that cannot be fully accessed but suggests that there is something to discover. The fountain follows the same geometrical language as the landscape beds, with a few layers of different heights. The tallest layer, a thick pillar-like structure, is the source of the fountain. From there, the water pours over select vertical faces of the fountain into the lower layers. There is a single path for the water to take from the highest layer to the lowest layer; this path is not immediately obvious, but its presence suggests that patterns exist upon closer observation.

The shape of the lower layers of the fountain uses the geometry I have used within the both the quantum mechanics exhibit hall and the theory of relativity exhibit hall to subtly imply that both theories are ultimately describing the same thing. The southern portion of the fountain, closer to the quantum mechanics exhibit hall, is slightly smaller, more orthogonal and broken up into more pieces to give a sense of hierarchical order and discontinuity. The northern portion of the fountain, closer to the theory of relativity exhibit hall, is slightly larger, more continuous, and less orthogonal to imply a larger scale and warping of geometry.

The northwest side of the fountain is shaped to create a more open area to welcome visitors in towards the fountain and towards the entrances of the existing buildings to the west of the site. The majority of the fountain is not directly visible from this approach, as the landscape bed hides the fountain's lower portion. This serves to enhance a sense of mystery. Reflections from the water on the higher portions of the fountain, however, hint that there is something to be revealed.

To the east of the fountain are two platforms accessible via stairs. A single apple tree, as well as a series of small boulders, are placed here to reference Newton's theory of gravity, the precursor to modern ideas of gravity (see **Figure 114**).

Figure 107
Key plan showing location of west garden



The approach to the museum is a wide, long pathway sheltered by an extended roof overhang at the rear entrance to the building. The main mass of the fountain is in line with the path to the fountain inside the building so that it can be seen in the distance from the interior.

Figure 108
Plan showing west garden

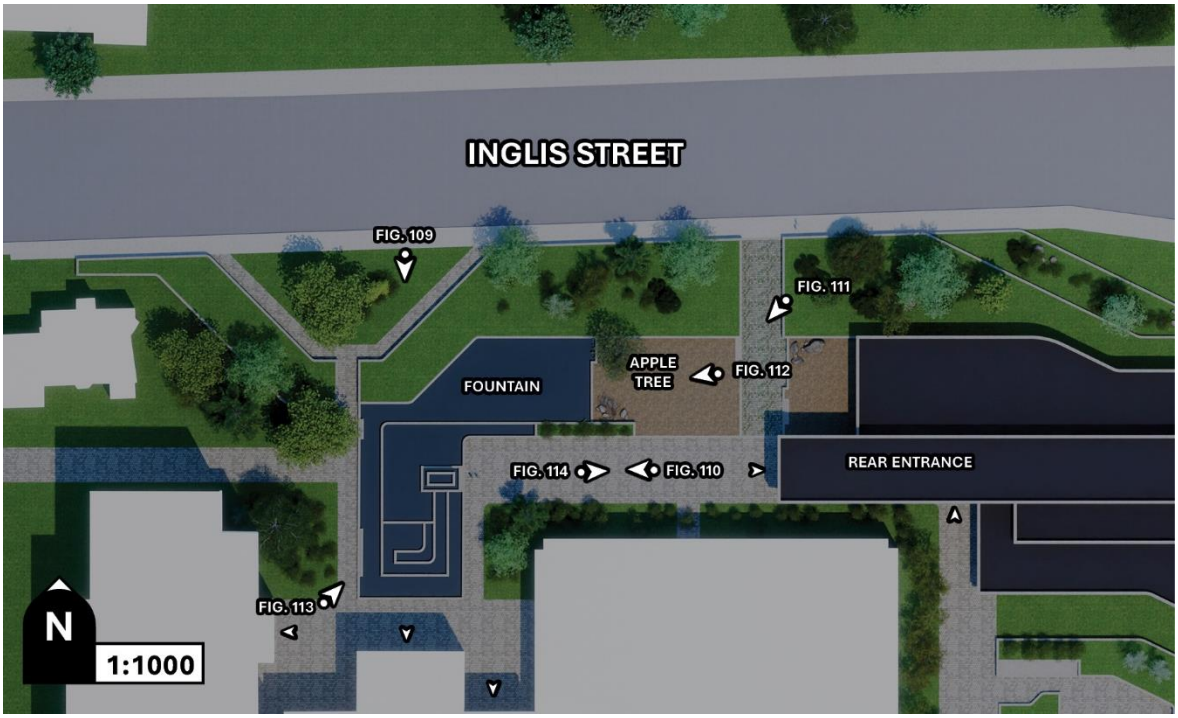


Figure 109
View of fountain, approached from the north



Figure 110
View of fountain, approached from the east



Figure 111
View of west garden



Figure 112
View of rear apple tree in west garden



Figure 113
View of exterior fountain



Figure 114
View of rear entrance from west garden



7.4 CENTRAL SPACE

7.4.1 ORGANIZATION AND LAYOUT

The shape of the central interior space of the museum is created by the gap between the lines of movement north, south, and east of it. The form of the main entrance continues deeper into the central space to extend its implied movement and to bring a sense of the exterior inside. This gesture comes to a head at a central interior fountain (see **Figure 122**).

The walls separating the central space from the exhibit halls are articulated to create variation. For the wall of the relativity exhibit hall, the width of these insets increases from west to east to subtly imply the stretching of space that the theory of relativity describes. The spacing of the insets into the wall of the quantum mechanics exhibit hall is more regular; this, paired with the consistency of the ratio between the insets and the extrusions of the wall, serve to impart a sense of structured organization and an interest in regular, repeating proportions.

Figure 115
Key plan showing location of central space

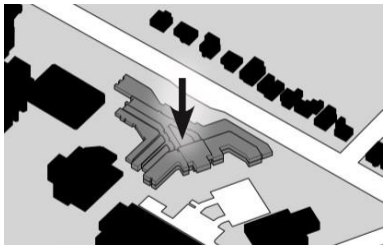


Figure 116
Central space of the museum interior



Figure 117
Common area accent wall for the theory of relativity exhibit hall

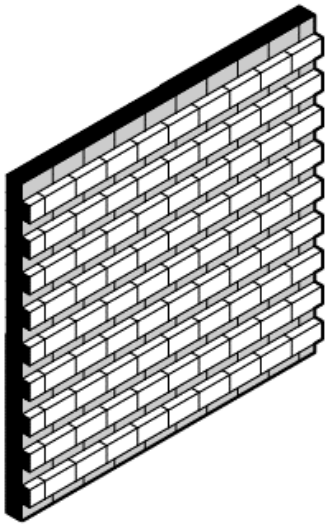
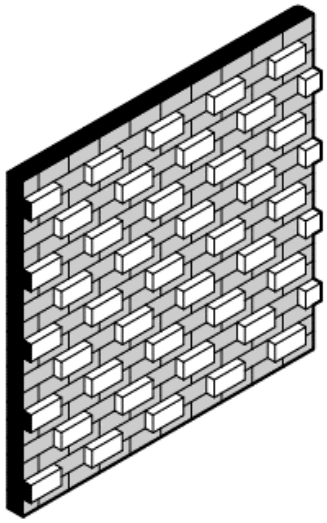


Figure 118
Common area accent wall for the quantum mechanics exhibit hall



WALL TEXTURES

The brick pattern of these insets is different than the regular running bond. The lower portions of the walls are given a unique texture, on both the side of the common area closest to the theory of relativity exhibit hall and on the side of the common area closest to the quantum mechanics exhibit hall. The textures are intended to both express a key concept within the relevant theory of physics, and to provide a greater sense of tactile materiality.

The accent texture for the wall closest to the theory of relativity exhibit hall evokes the idea of continuity and movement. The bond pattern consists of layers of horizontal brick stacked such that each second layer is inset deeper into the wall (see **Figure 117**). The protruding layers are the typical lighter brick colour, while the inset layers are the typical darker brick colour. Both brick types here are of the same dimensions.

The accent texture for the wall closest to the quantum mechanics exhibit hall evokes the idea of objects against a background of space. The pattern is a diagonal grid of offset protruding bricks (see **Figure 118**). Like the theory of relativity accent wall, the protruding bricks are the typical light brick colour, and the inset bricks are the typical darker brick colour. Again, both brick types here are the same size.

LIGHT FIXTURES

Strip lights along the edges of the common area are used to emphasize the broad lines and forms of the building (see **Figure 122**).

Figure 119
View of the accent brick pattern for the theory of relativity exhibit hall.

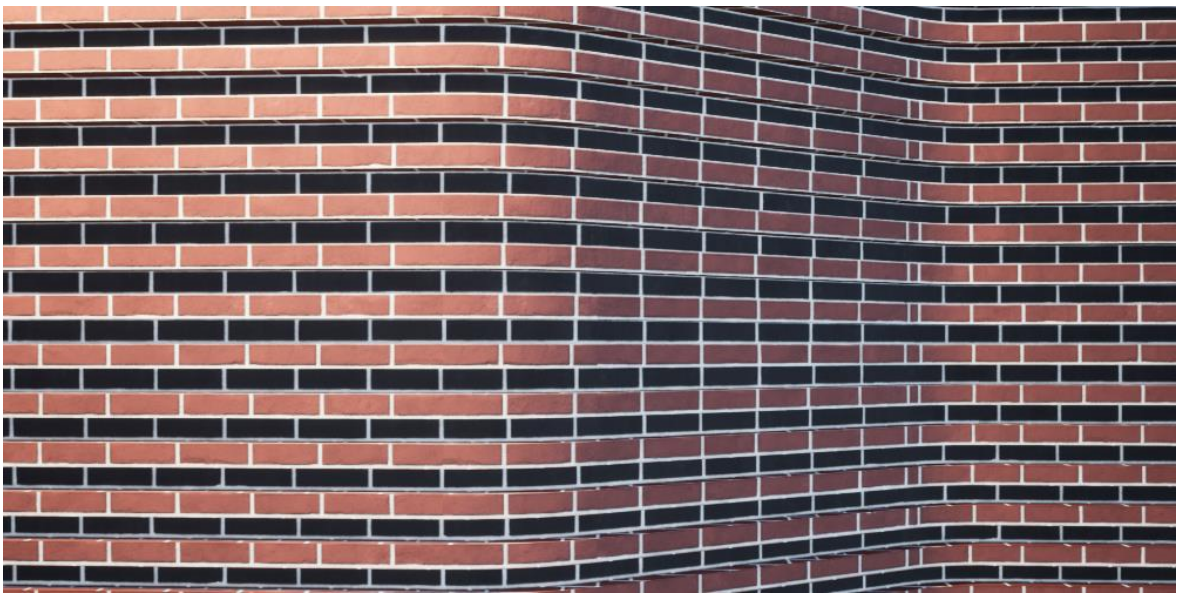


Figure 120
View of the accent brick pattern for the quantum mechanics exhibit hall.

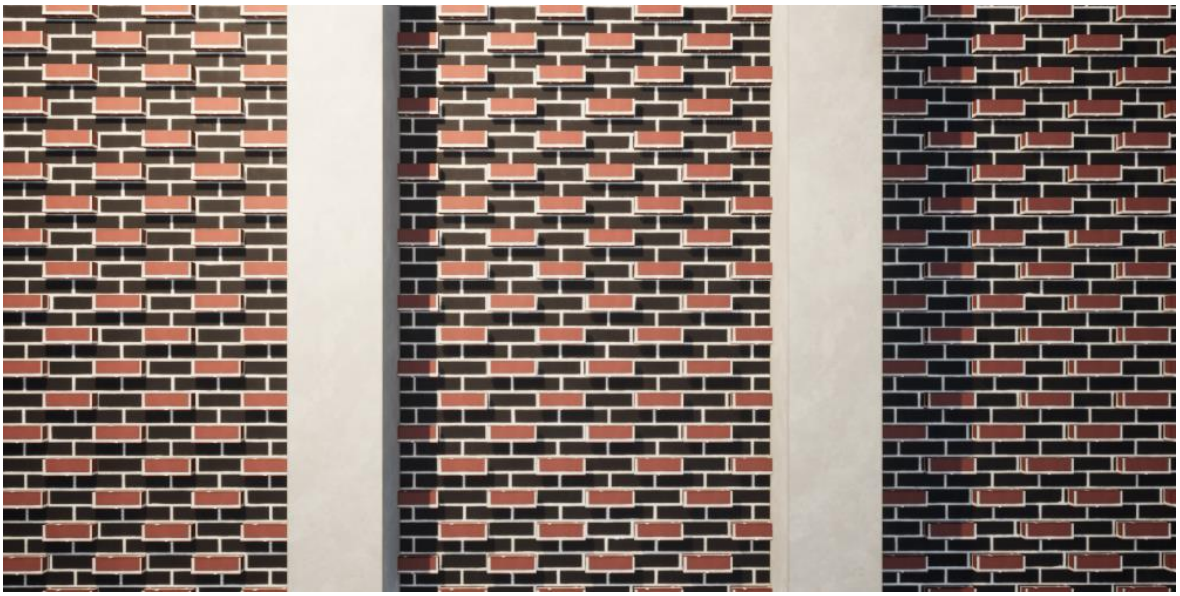
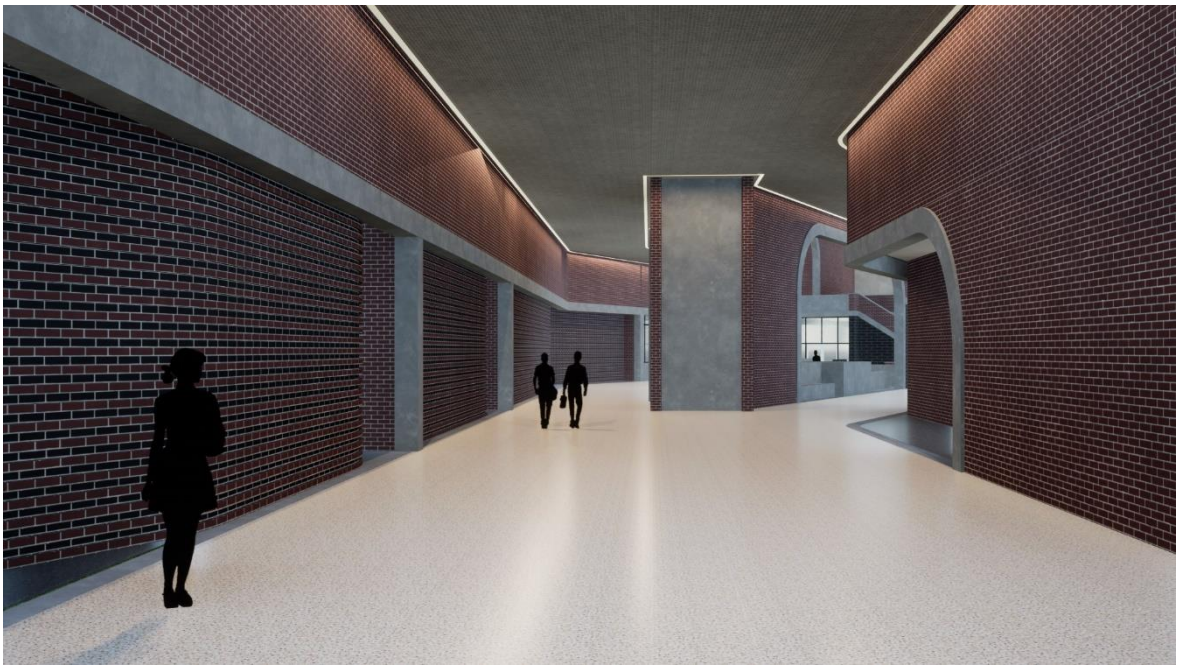


Figure 121
View of central space near front entrance



Figure 122
View of central space facing east from rear entrance



7.4.2 MAIN ENTRANCE

From the exterior, the concrete faces of the main entrance appear to rise up towards the centre above the entrance doors (see **Figure 125**), an effect similar to the niches in the interior of S. Carlo alle Quattro Fontane (see **Figure 9** in **section 3.4**). The offsetting of the concrete and the glazing on these faces also gives the sense of being blocked off in some directions and not in others; this provides a subtle sense of searching for the direction in which to enter the interior.

The interior of the entrance begins with a vestibule both for creating a longer, gentler threshold condition and for climate control.

Figure 123
Key plan showing location of main entrance

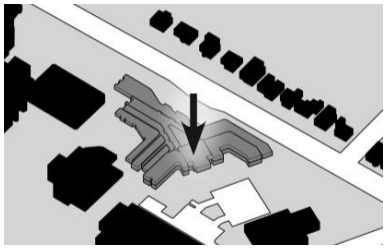


Figure 124
Plan of main entrance



Figure 125
View of main entrance exterior



Figure 126
View of main entrance interior



7.4.3 EXHIBIT HALL EXITS

The string theory and loop quantum gravity exhibit halls both exit to the same platform above the main entrance. Their paths join together and return to the area in front of the information desk.

Figure 127
Plan of exhibit hall exits

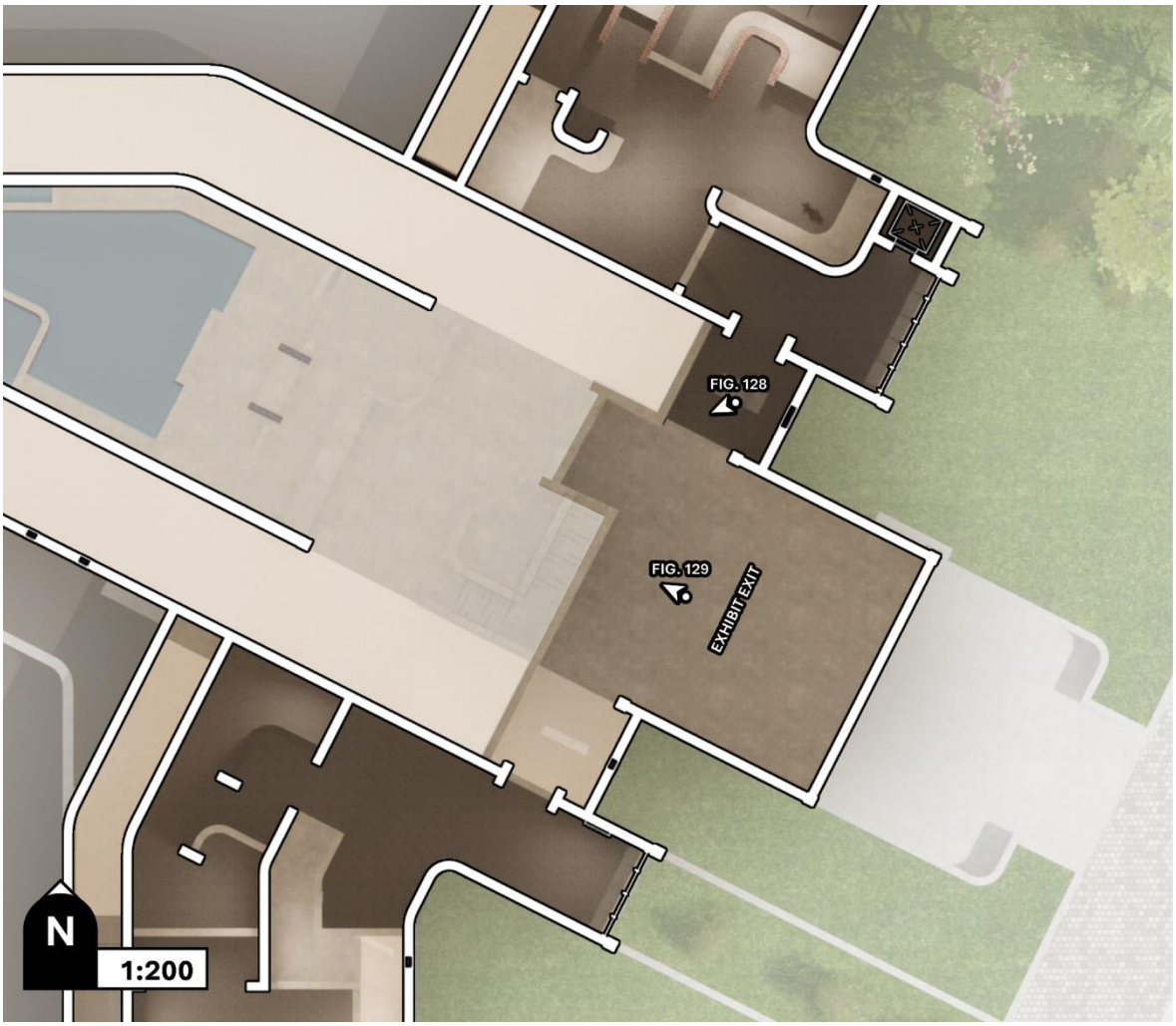


Figure 128
View of exhibit hall exits



Figure 129
View of exhibit hall exits facing east



7.4.4 INFORMATION DESK

The information desk is immediately visible upon entering the museum through the main entrance and is quickly visible upon entering the museum through the rear entrance. The desk has higher and lower levels for accessibility. A prominent vertical slab provides space for signage; its placement towards the rear of the information desk draws visitors further into the building.

The information desk stretches between two pillars, just below a change in ceiling level. The ceiling height immediately surrounding the main entrance is two storeys, while from the information desk to the rear entrance the ceiling is closer to one-and-a-half storeys. Both near the main entrance and past the information desk, the ceiling level is slightly higher towards the middle of the common area of the museum, and slightly lower towards the walls connecting the common area to the exhibit halls.

The higher central portion of the ceiling behind the information desk leads towards the fountain behind the information desk and serves to open up the interior common space. A window at the change in height of the central strip of the ceiling, from the two-storey section of the roof near the main entrance to the one-and-a-half storey section of the roof past the information desk, features a window to bring in light, draw attention to the information desk, and to imply partial continuity between the two ceiling heights.

Figure 130
Plan showing information desk

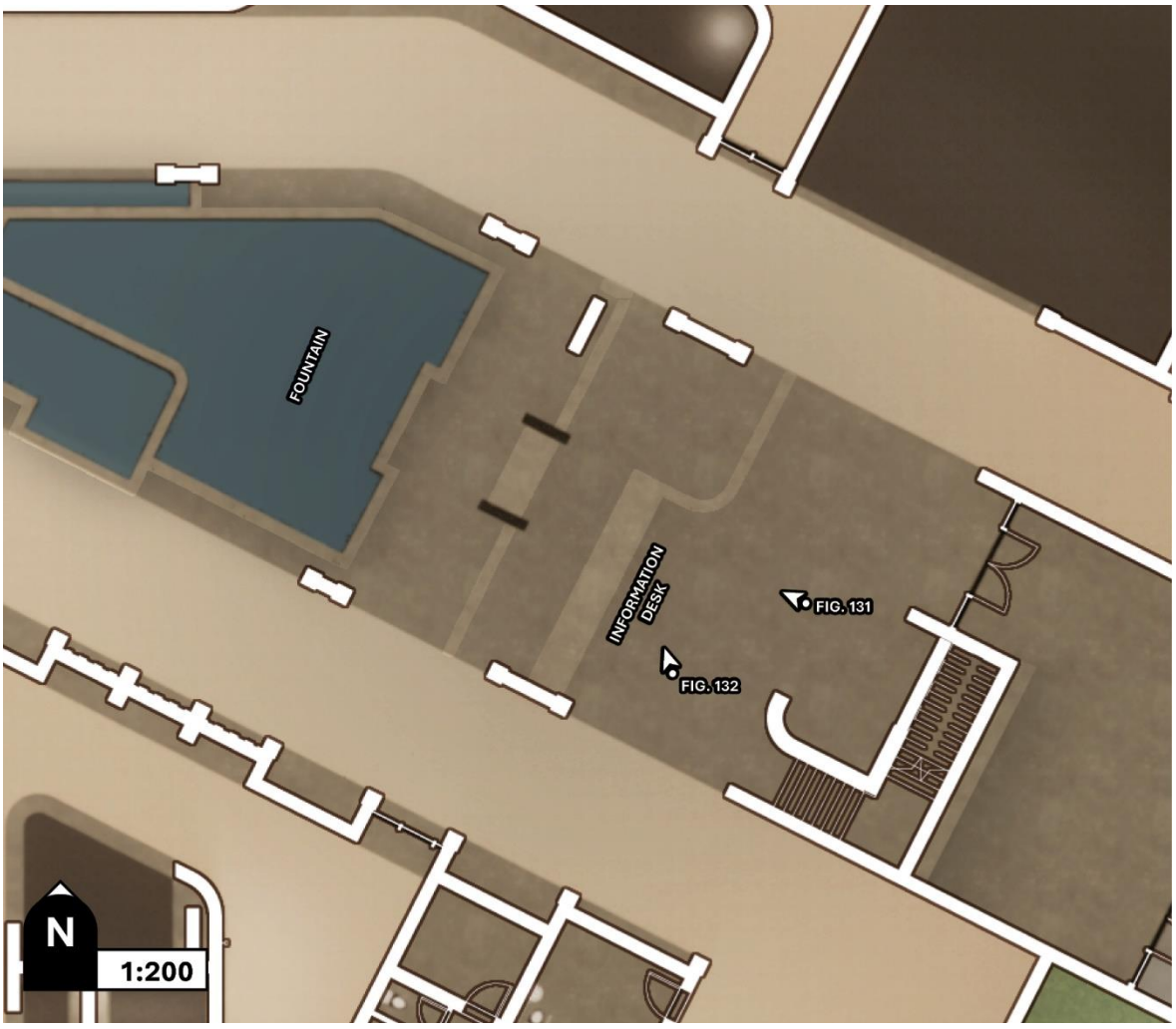


Figure 131
View of information desk from above



Figure 132
View of information desk



FOUNTAIN

The interior fountain follows the same architectural language as exterior fountain and landscape beds to bring features of the exterior into the interior. Like the exterior fountain, it has its source at a higher pillar-like structure. Also similar is how the interior fountain is more articulated on the side closer to the quantum mechanics exhibit hall and smoother on the side closer to the relativity exhibit hall. The two largest segments of the fountain—one closer to the quantum mechanics exhibit hall and the other closer to the theory of relativity exhibit hall—are not connected directly by the flow of water, while they are both fed from the same source; this references that the two theories have not been successfully combined, but that they are both interpretations of the physical world.

Built-in benches are inset into the side of the fountain to allow for visitors to comfortably spend time absorbing the atmosphere close to the water.

The falling water, the ripples in the basins, and the point at which the water goes from one to another all act in contrast with each other.

Figure 133
Plan showing fountain in central interior space

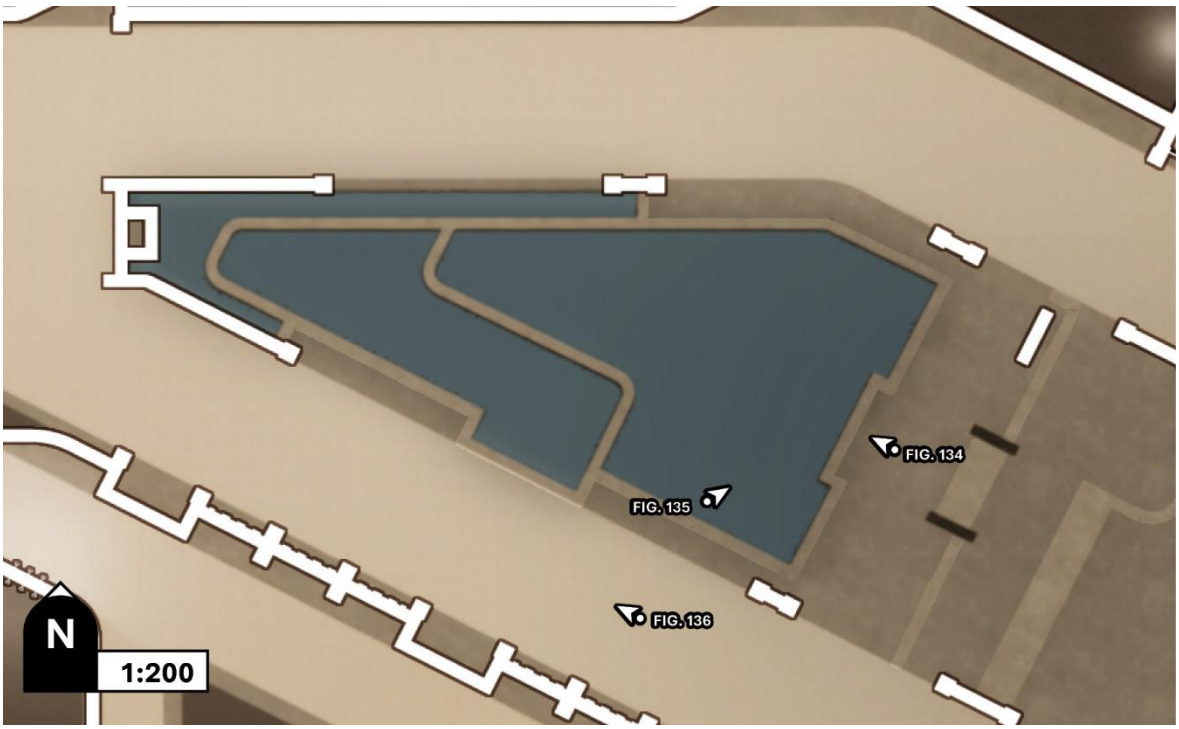


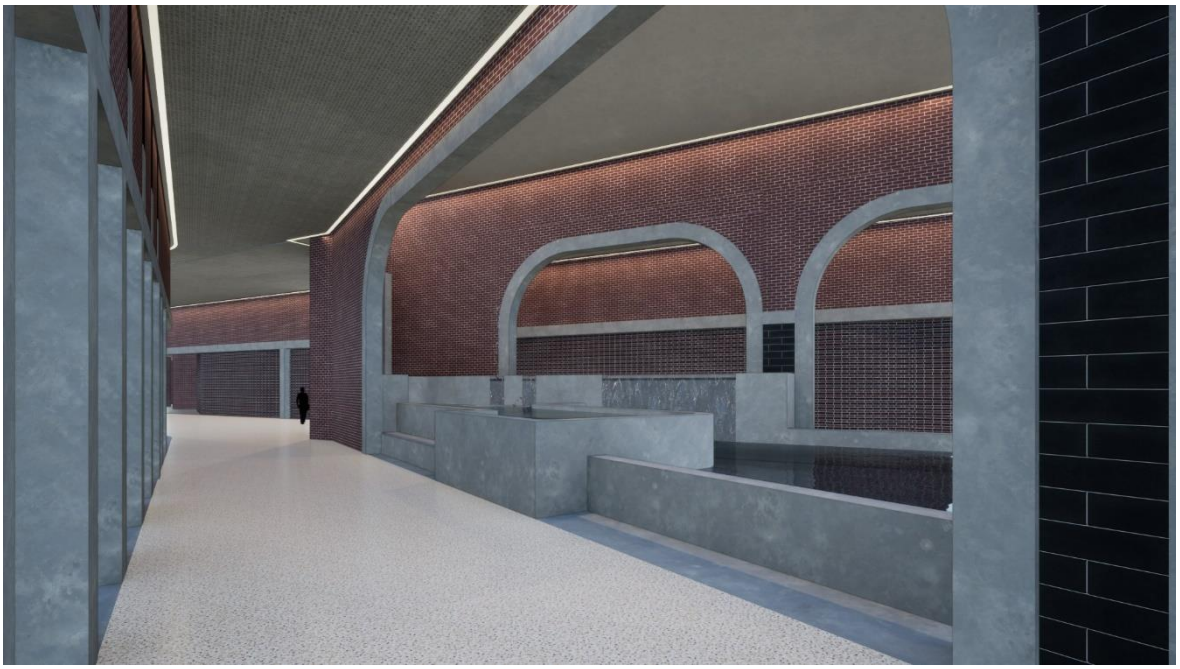
Figure 134
View of fountain



Figure 135
View of edge of fountain and information desk



Figure 136
View of fountain



7.4.5 REAR ENTRANCE

At the exterior of the rear entrance, the roof extends significantly over the pathway (see **Figure 140**). This roof extension serves dual purposes of making the rear entrance more secluded, while also signalling its location to visitors approaching from directions in which the rear entrance cannot be directly seen, such as from the southwest garden.

Figure 137
Key plan showing location of rear entrance

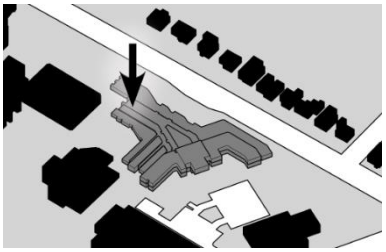


Figure 138
Plan showing rear entrance

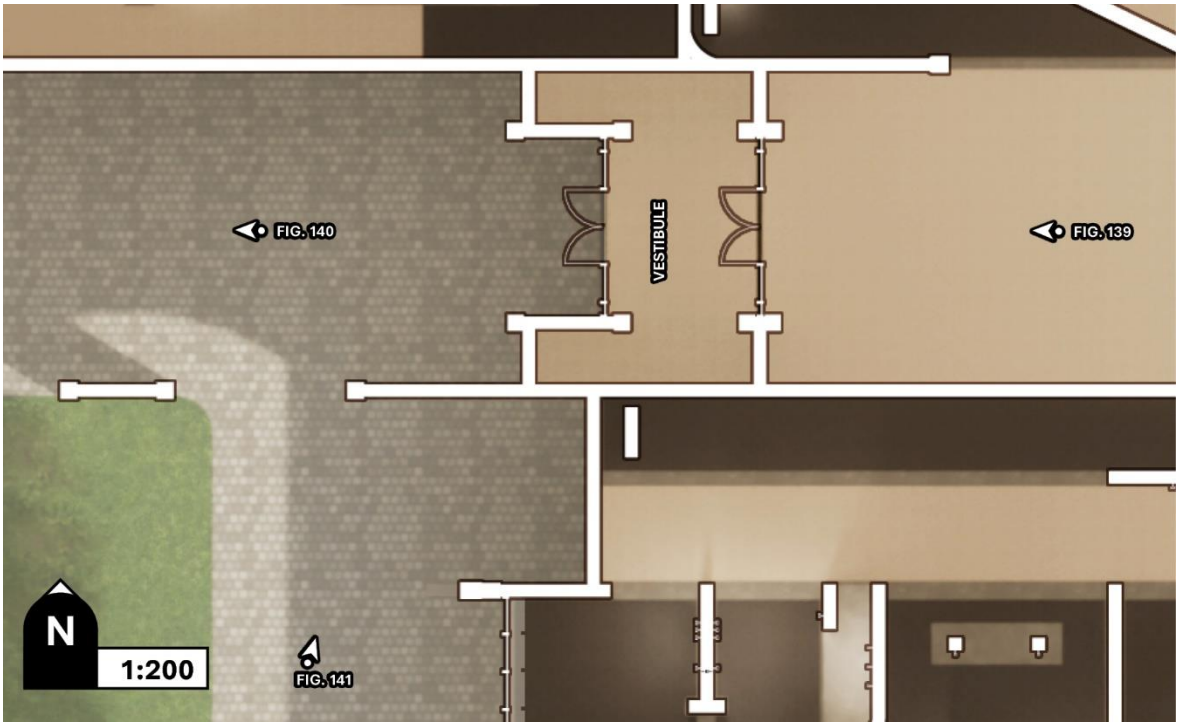


Figure 139
View of rear entrance from interior

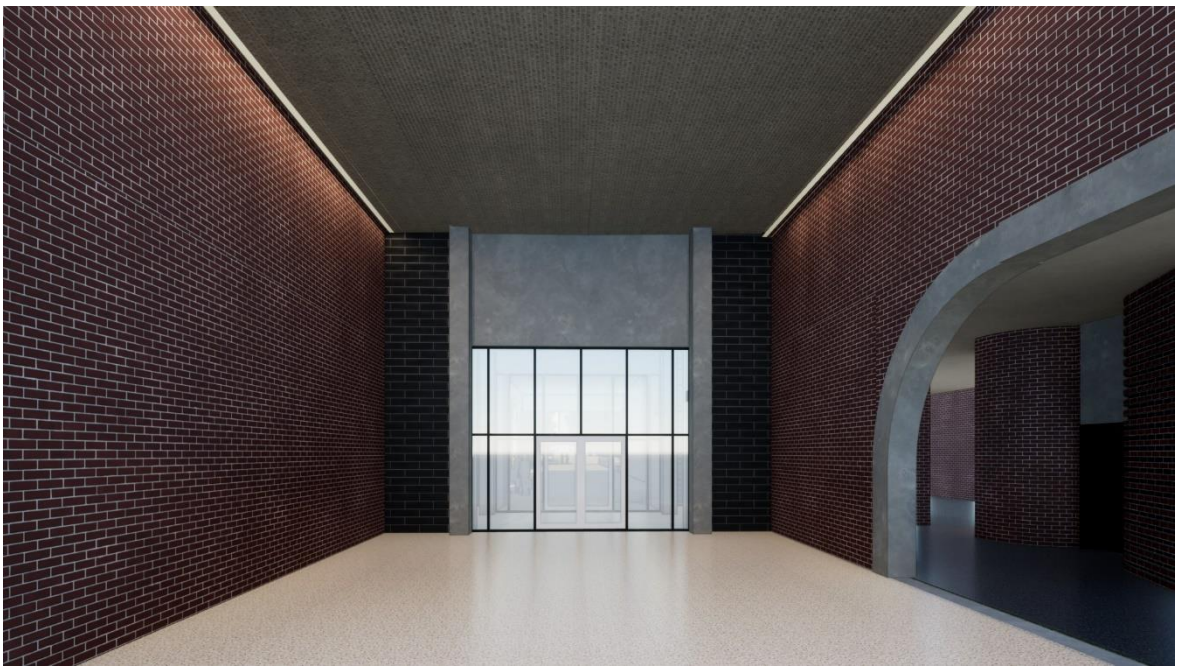
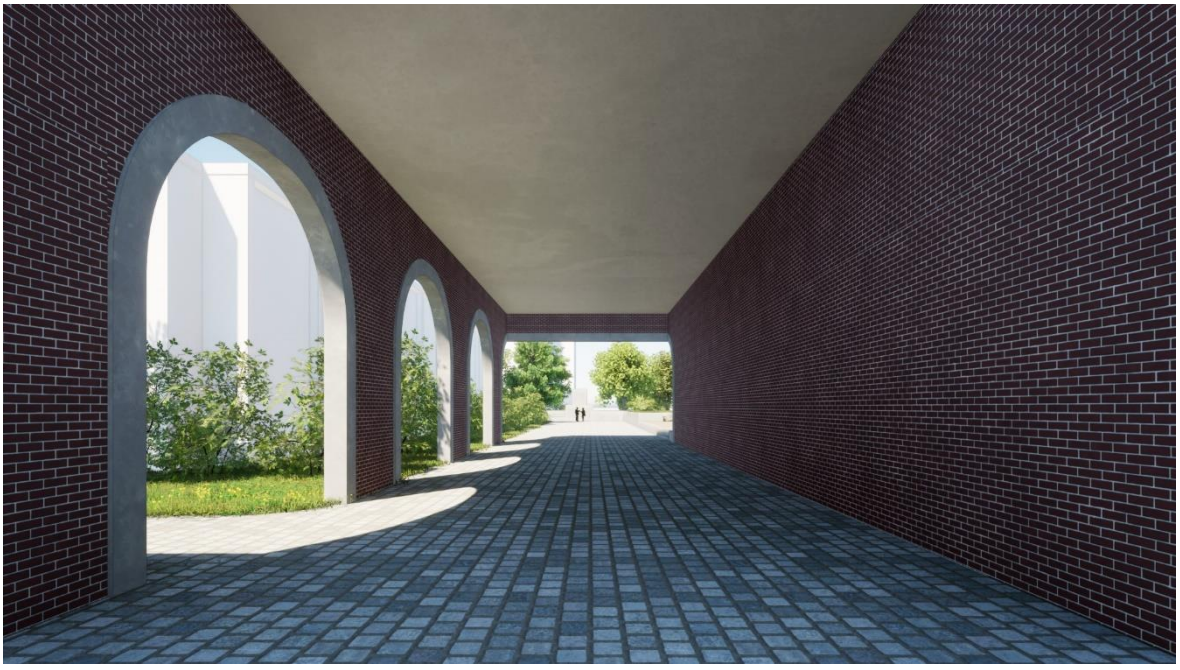


Figure 140
View of rear entrance from exterior



Figure 141
View of canopy over exterior of rear entrance



7.4.6 WASHROOM

The washroom is located to the south of the main entrance. It, and the staff room, are connected to the main central area via a short, wide corridor. There is a universal accessible washroom to the north of the main washroom.

7.4.7 STAFF AREA

The staff area is to the south of the washroom. It has one large general-purpose room and two smaller rooms that could be used as storage or office space. A staff entrance on the south wall leads outside to the staff parking lot.

Figure 142
Key plan showing location of washroom and staff area

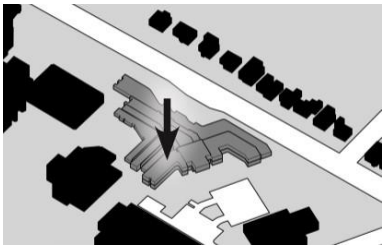


Figure 143
Plan showing washroom and staff area



Figure 144
View of entrance to staff room and washroom hallway



Figure 145
View of staff room



7.4.8 DISPLAY ROOM

To the northeast of the main entrance is a large room intended to house rotating temporary displays and exhibits. To accommodate a variety of possible layouts, the floor space is kept relatively clear.

The ceiling just inside the entrance to the display room is slightly raised and then after a short distance slightly lowered; this is to create a less abrupt threshold condition. The ceilings at the northeast edges of the room are likewise slightly lowered to create more secluded areas without interrupting the floorspace.

Figure 146
Key plan showing location of display room

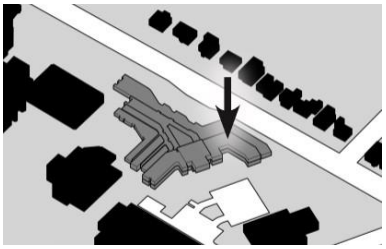


Figure 147
Plan showing temporary display room



Figure 148
Reflected ceiling plan of temporary display room



Figure 149
View of entrance to display room



Figure 150
View of display room



7.5 RELATIVITY

7.5.1 ORGANIZATION & LAYOUT

The relativity exhibit hall can be divided into three main sections: foundational concepts, special relativity, and general relativity, in that order. These are organized spatially as a single path, one after another; there being a single path of movement through this exhibit hall is intended to accentuate a feeling of continuity and smoothness, as well as to focus the architectural experience on the space as an enclosure rather than on any dividing interior walls. Additionally, this single-path organization serves to avoid a sense of obvious hierarchical order within the architecture.

The overall design of the architectural elements within the relativity exhibit hall is intended to express the idea of the warping and stretching of space. As such, the architectural choices typically involve inflecting the enclosing walls, floor, and ceiling to create spaces, as well as keeping interior walls attached to the main enclosing walls to maintain the impression that the space surrounding you is warping. This strategy, however, does not begin to apply until the idea of space and time stretching is introduced, *after* the introductory material.

Figure 151
Key plan showing location of Relativity exhibit hall

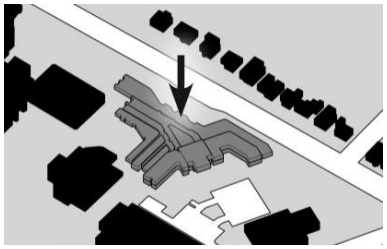
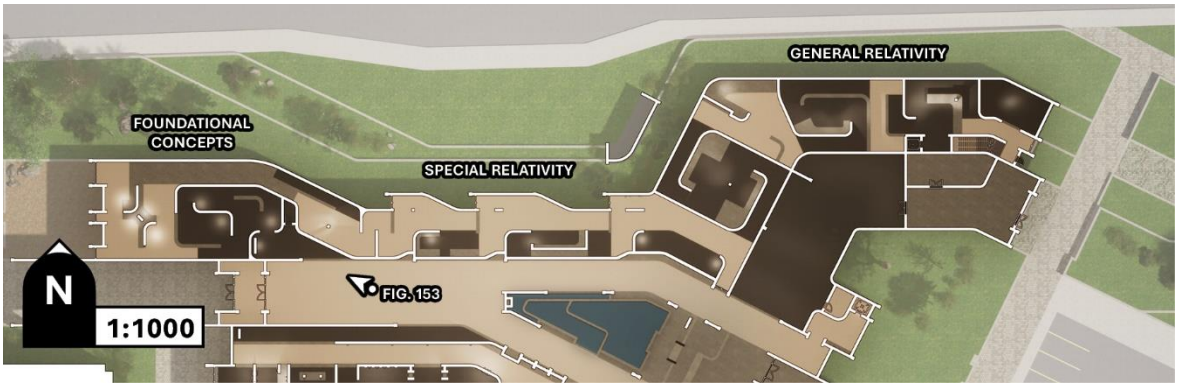


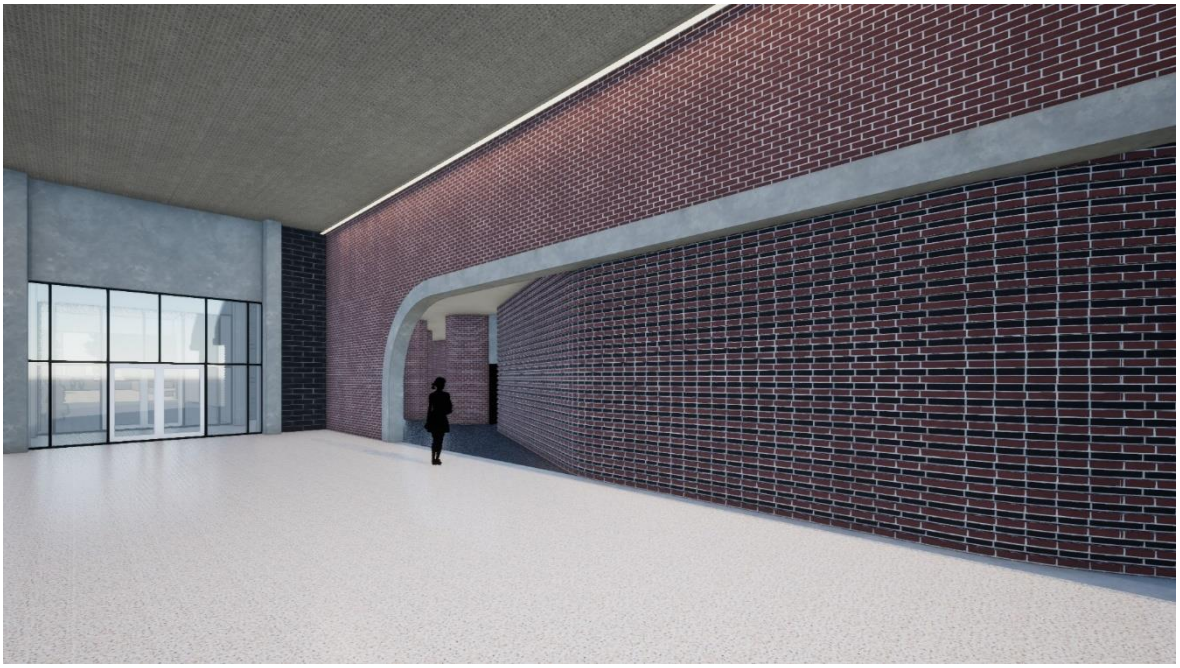
Figure 152
Plan of theory of relativity exhibit hall



7.5.2 ENTRANCE

The entrance to the relativity exhibit hall is announced via the curving of a wall in the common area that leads visitors towards an entrance display. The curvature of the walls references the discovery of the warping of spacetime in the theory of relativity.

Figure 153
View of entrance to theory of relativity exhibit hall



7.5.3 FOUNDATIONAL CONCEPTS

WAVES AND THE LUMINIFEROUS AETHER

Immediately following the entrance is the exhibit area about waves and the luminiferous aether. The walls here curve to suggest wavelike forms.

Figure 154
Key plan showing location of foundational concepts for relativity exhibit area

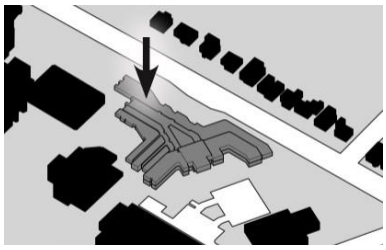


Figure 155
Plan showing waves and luminiferous aether exhibit areas

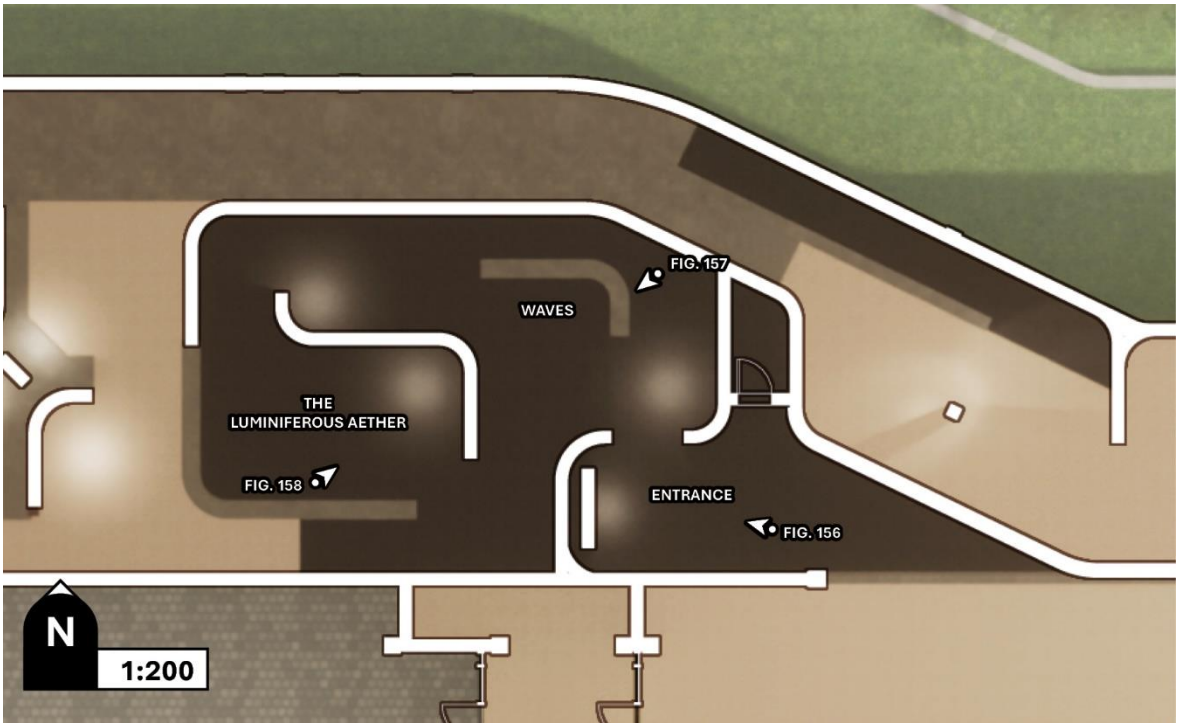


Figure 156
View of entrance signage to the theory of relativity exhibit hall

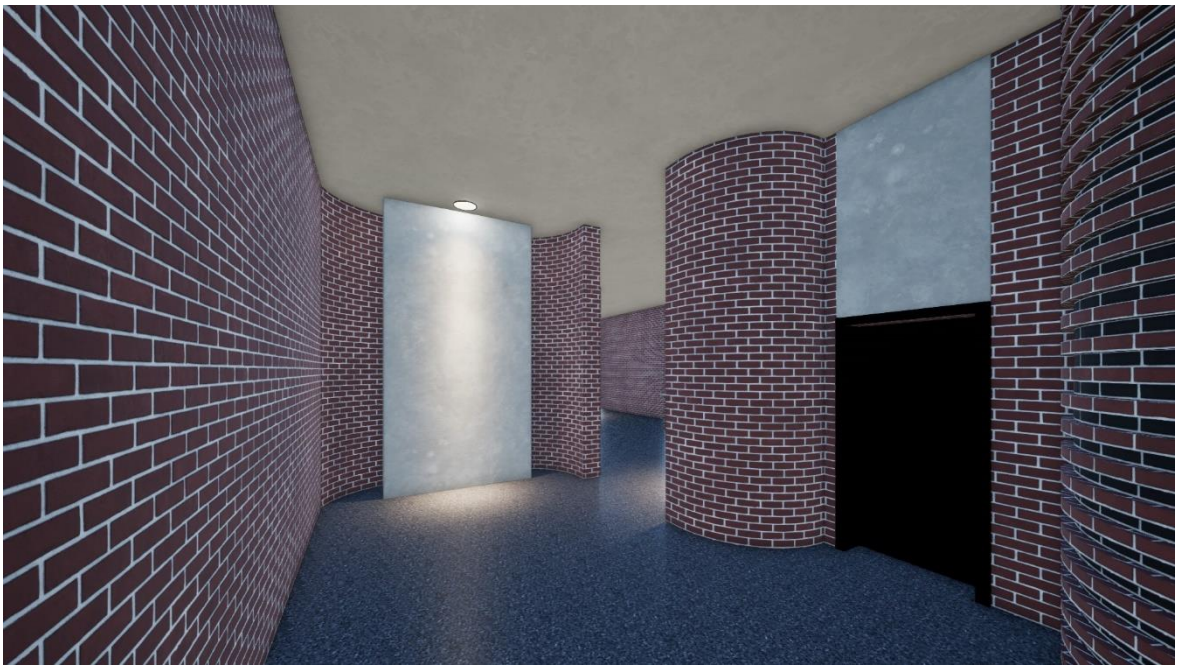
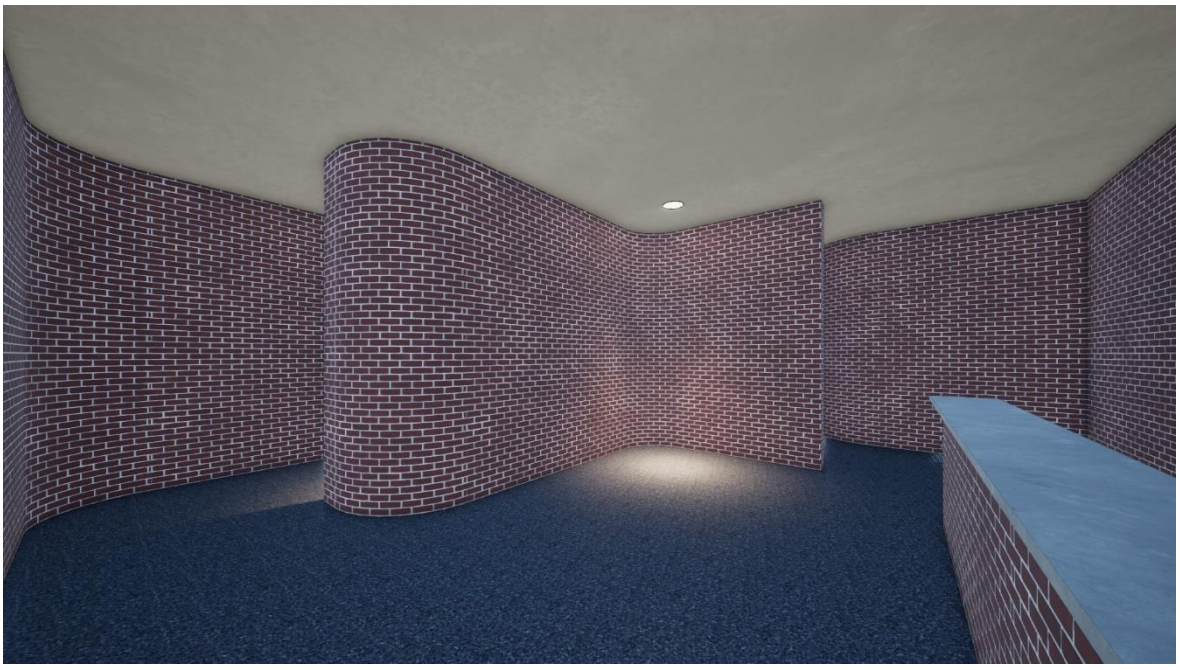


Figure 157
View of the luminiferous aether exhibit area



Figure 158
View of the luminiferous aether exhibit area



THE TRUE SPEED OF LIGHT

The exhibit area about the luminiferous aether transitions into this exhibit area, about the true speed of light, with a short downwards ramp that serves to slightly open up the distance between the floor and the ceiling to impart a sense of discovery. This effect is emphasized with light coming from the window directly facing the ramp.

This exhibit area is intended to house exhibits that explain the Michelson-Morley experiment and its variation, the Kennedy-Thorndike experiment. Both of these experiments rely on using interference patterns of light to examine light's behaviour, and so I highlight this in the architecture. Two L-shaped walls are oriented so that their corners face each other, and the placement of a pillar brings attention to this "interference point" in the gap between the two walls. A window, too, lines up with this interference point to further bring attention to it.

The transition from the exhibit area about the speed of light to the exhibit area about special relativity begins with a long hallway to introduce a sense of speed. The spacing of windows along the north wall increases as visitors pass them to emphasize the sense of speed further.

Figure 159
Plan showing the speed of light exhibit area

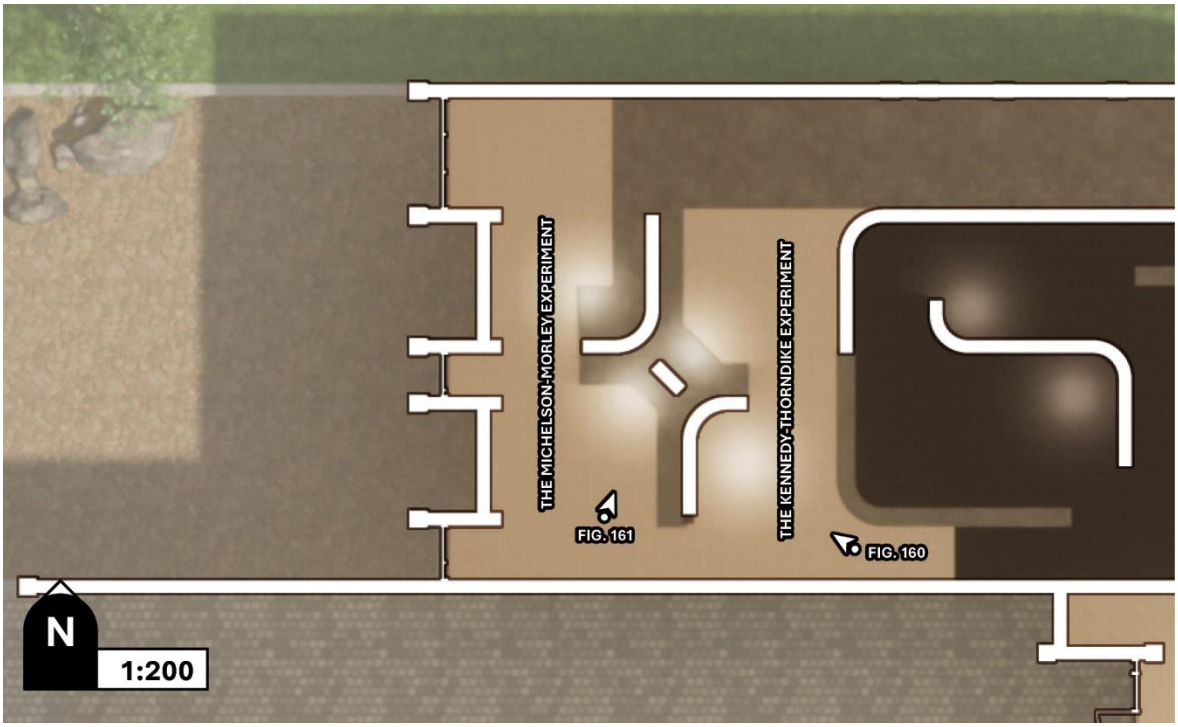


Figure 160
View of the approach to the speed of light exhibit area



Figure 161
View of central part of the speed of light exhibit area



7.5.4 SPECIAL RELATIVITY

ORGANIZATION AND LAYOUT

Following the foundational concepts exhibit area is the exhibit area about special relativity.

Special relativity relates to the behaviour of space, time, and matter at speeds approaching the speed of light. This exhibit area is organized around a long, straight gesture with an unblocked sightline through its entire length, to impart the sense of the speed and motion explored within this exhibit area.

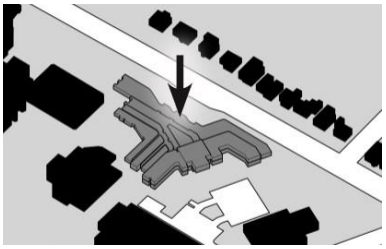
Despite the unbroken sightline through the main axis of this exhibit area, visitors cannot travel straight through as they are blocked and directed by partial-height walls (see **Figure 165**). These walls act to create tension between the visitors' ability to *see* a straight path through the exhibit hall, but their inability to *move* in a straight path through the exhibit hall; this tension calls attention to the sensation of movement. Additionally, the bouncing back and forth and switching of empty space and walls along this sightline is evocative of the bouncing of light used in many of the thought experiments of special relativity.

To the southern side of the special relativity exhibit area are three more sheltered rooms for more specific exhibit areas. Each of these areas is slightly hidden from view by walls to their west sides, which elicits a subtle sense of mystery and discovery, but are open towards their east sides, which maintains the sense of a mostly continuous space.

To the northern side of the special relativity exhibit area are three windows. Each of these is placed on the angular side of a curved sawtooth shape, oriented towards the west. The windows are thus only visible *after* a visitor has passed them, and even then are only visible when the visitor turns around to look back the way they came from. Any shadow from the windows, too, will lie in *front* of the visitor's main path of travel, reminiscent of how we can see our shadows stretching in front of us at sunset. These factors combined emphasize the passage of time.

Both the rooms at the southern side and the sawtooths at the northern side vary in length to stress the sense of space and time stretching.

Figure 162
Key plan showing location of special relativity exhibit area



The ceiling here is made up of two textures: smooth and grooved. The grooved texture flows from the windows, along the sawtooths, and then along the main gesture of the special relativity exhibit area (see **Figure 164**), to accentuate both the main gesture and the sense of space being mutable.

Figure 163
Plan showing the special relativity exhibit area

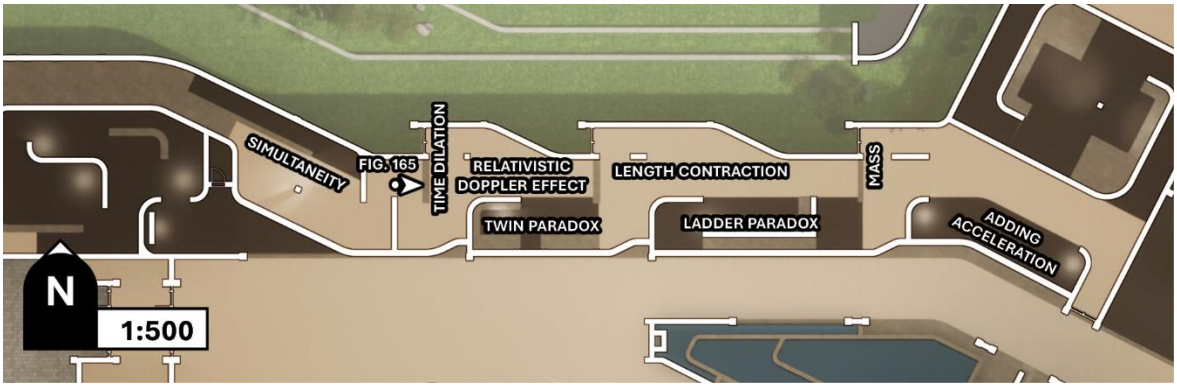


Figure 164
Reflected ceiling plan showing the special relativity exhibit area

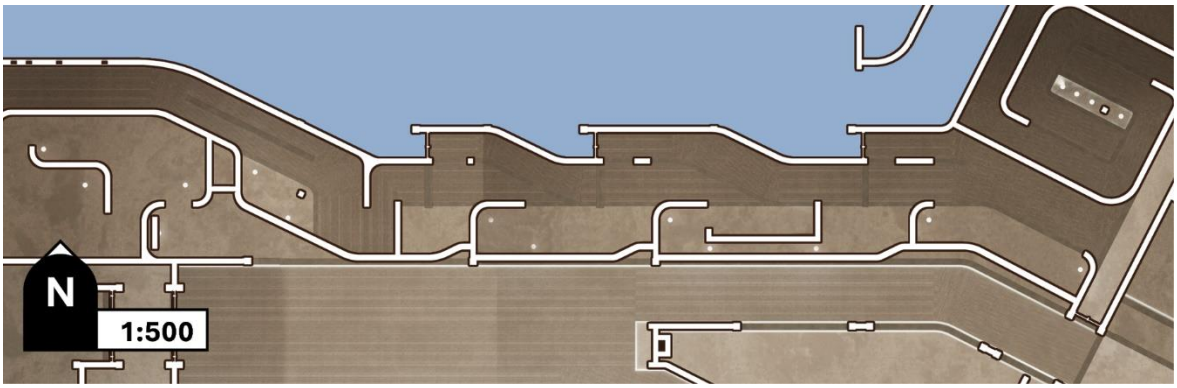


Figure 165
View of special relativity exhibit hall, looking down the main sightline



SIMULTANEITY

The first exhibit area within the special relativity exhibit area is about simultaneity.

To express the idea of two different observers experiencing the same event differently, two methods of ascending a change in floor level are used: a stair and a ramp. Due to the difference in the amount of horizontal space the stair and the ramp require, they are staggered with respect to each other. This difference is accentuated by locating the stair and the ramp parallel and adjacent to each other.

Visitors exiting from the stair and from the ramp then approach, from different directions, a single pillar. Multiple spotlights are aimed at this pillar to create shadows in multiple directions, as if the gnomon of a sundial was casting shadows at multiple times of day simultaneously.

Because simultaneity is foundational to the rest of special relativity, the transition between this exhibit area and the rest of the special relativity exhibit area is more gradual; the visual obstruction created by a couple of walls means that visitors cannot directly see the following exhibit areas, and can only infer their existence by the small connecting portion they can see. This hint of what is to come suggests that a discovery is approaching.

Figure 166
Plan showing the simultaneity exhibit area

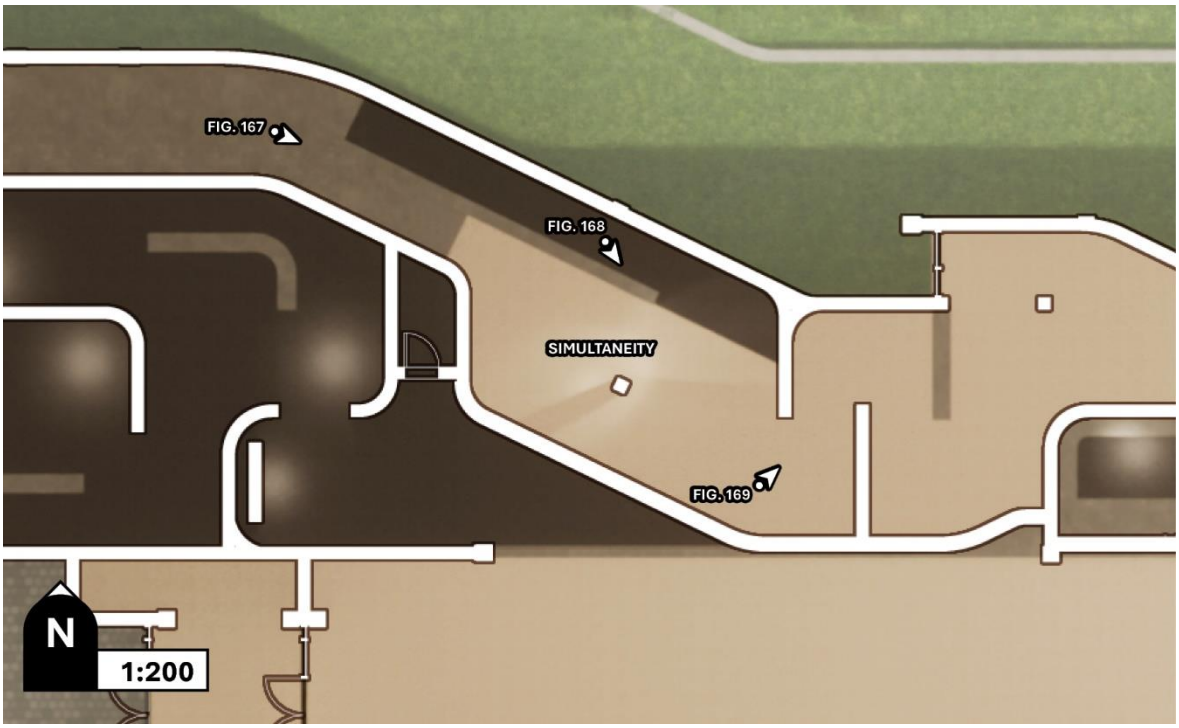


Figure 167
View of hallway leading to the special relativity exhibit hall

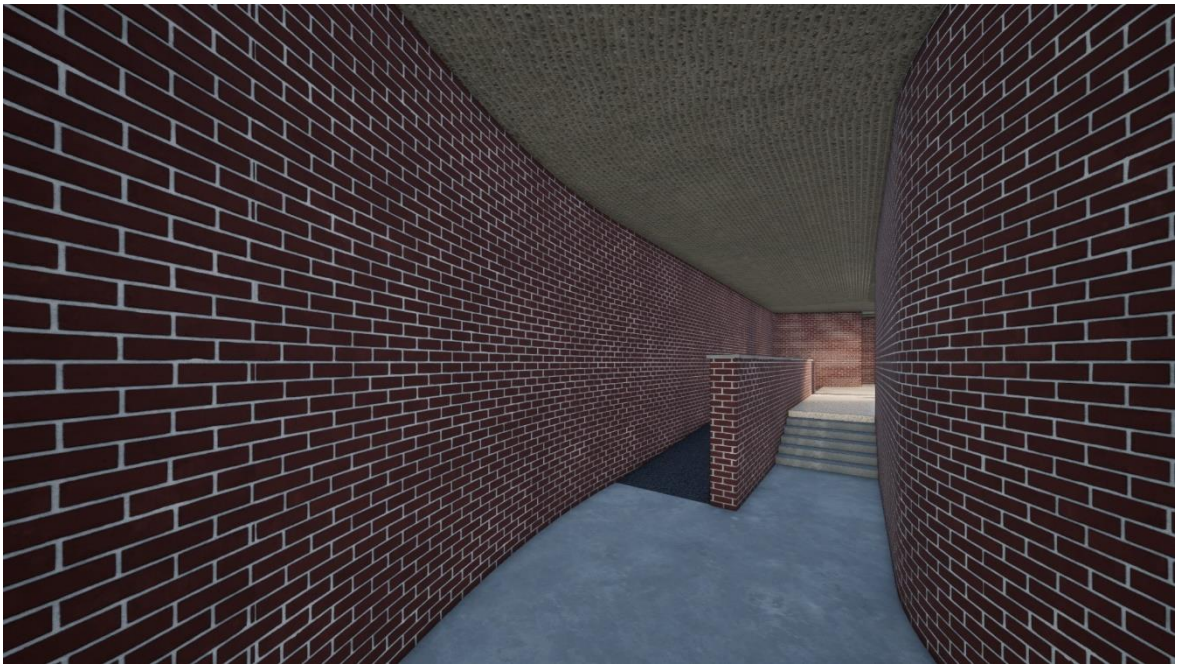


Figure 168
View of simultaneity exhibit area



Figure 169
View of simultaneity exhibit area exit



TIME DILATION AND THE RELATIVISTIC DOPPLER EFFECT

The first exhibit areas after the simultaneity exhibit area are those of time dilation and the relativistic Doppler effect. Like in simultaneity, a single column here is used to create overlapping "sundial shadows" to suggest the movement of the sun over time. This exhibit area also dips into the first sawtooth window, which takes visitors out of the main visual path of movement into a "slower" area, which subtly changes the sense of the speed of time being experienced.

THE TWIN PARADOX

To the south of the time dilation exhibit area is the twin paradox exhibit area. Two counters are placed to the south side of the exhibit area. The counters, unlike the columns, have different dimensions. One is a more typical rectangular counter, while the other is longer and curves around fully. This, along with the difference in column widths, is a reference to one twin in the paradox remaining on Earth and the other travelling and reversing direction.

Figure 170
Plan showing time dilation, relativistic doppler effect, and twin paradox exhibit areas

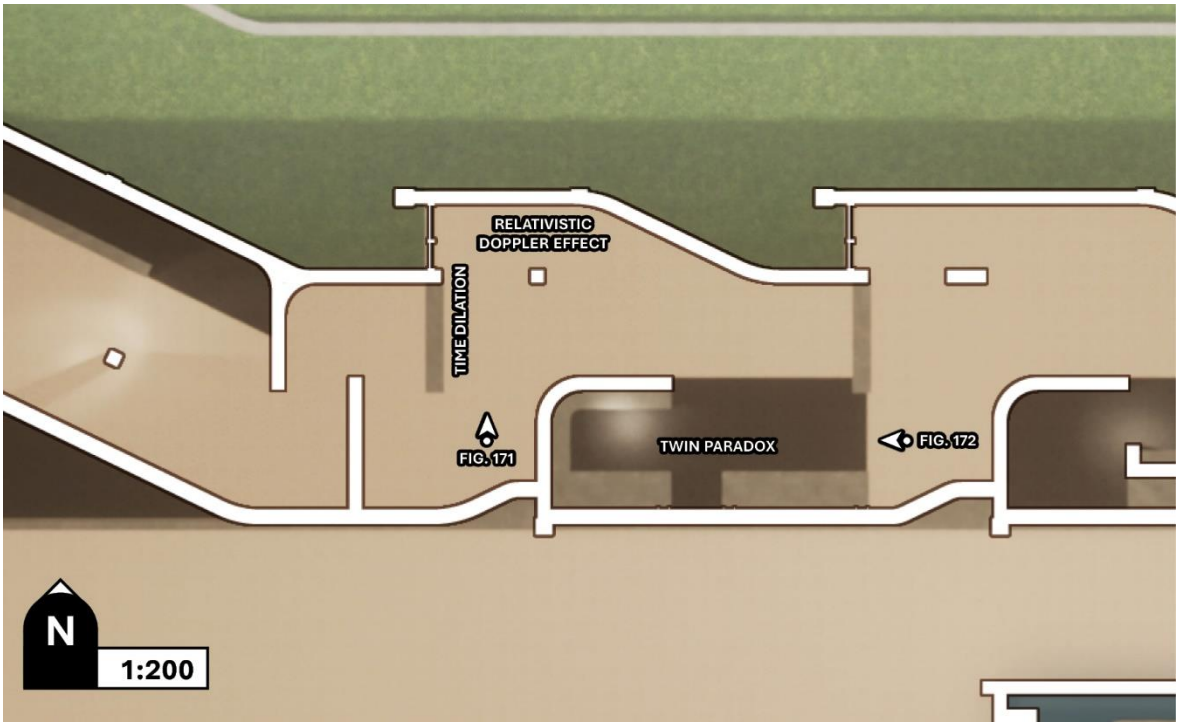


Figure 171
View of time dilation exhibit area



Figure 172
View of twin paradox exhibit area



LENGTH CONTRACTION

Like the time dilation exhibit area, the length contraction exhibit area is located within one of the sawtooths. Because this exhibit area's contents deal with the length of objects measured by observers in different frames of reference, the dimensions of the elements here are stretched: the sawtooth is longer, and the column is stretched to become a short wall.

THE LADDER PARADOX

To the south of the length contraction exhibit area is the ladder paradox exhibit area. To evoke the idea of running through the barn, a long, relatively narrow passageway is hidden behind a full-height wall. The passageway's presence is suggested to visitors by light coming out from both ends of the passageway.

Both ends of the passageway, too, feature a single step up. This is to draw attention to the moments at which visitors enter and exit the passageway, referencing the importance of understanding the relative order of events to resolving the ladder paradox. On the north side of the passageway's wall is a counter. Both ends of the counter are inflected at ninety-degree angles to further draw attention to the entrance and exit of the passageway.

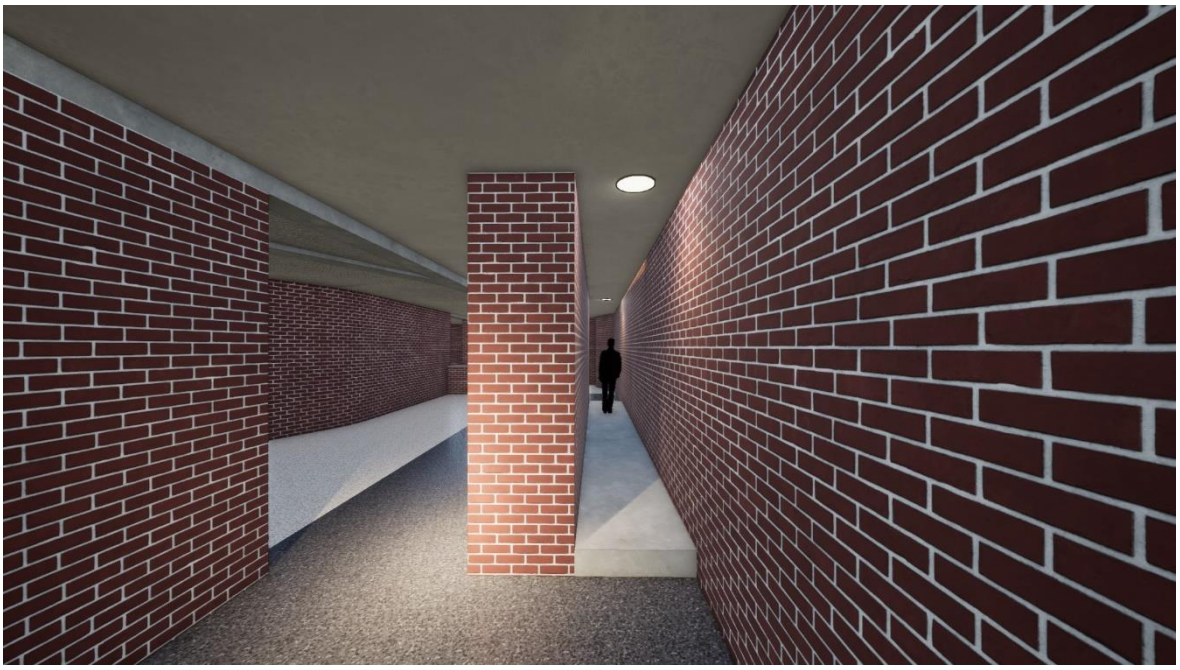
Figure 173
Plan showing length contraction and ladder paradox exhibit areas



Figure 174
View of ladder paradox and length contraction exhibit area



Figure 175
View of ladder paradox exhibit area passageway



MASS

The next exhibit area in the special relativity exhibit area is about the difference in relativistic mass measured by observers within different frames of reference. To suggest mass, the stretched-column wall here is the largest.

ADDING ACCELERATION

Mass is a central part of the theory of general relativity, and so this exhibit area also acts as a transition from special relativity to general relativity. In the same area as the exhibit area about mass increase is the exhibit area about introducing the idea in general relativity that acceleration and gravity—which is related to mass—are indistinguishable.

The addition of acceleration into relativity is what forms the transition of the special case of relativity to the general version of relativity. To express this transition, the special relativity exhibit area begins to twist around and follow the curved architectural language of the general relativity exhibit area.

Figure 176
Plan showing mass and adding acceleration exhibit areas

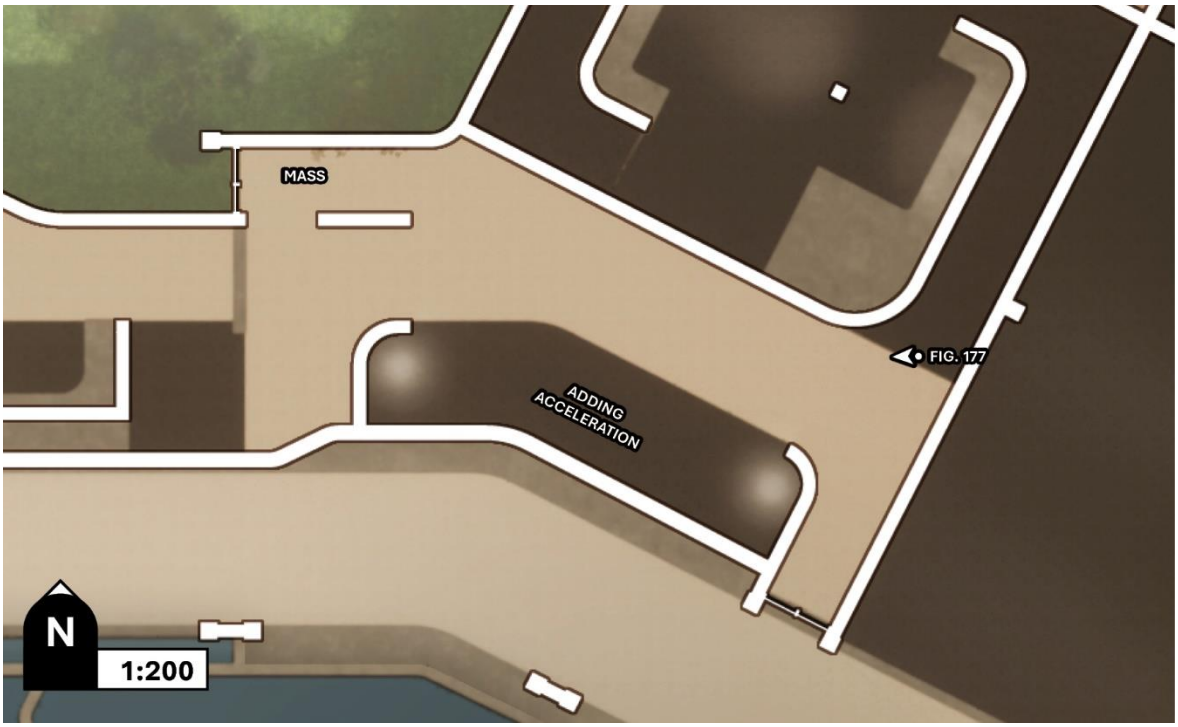


Figure 177
View of mass and adding acceleration exhibit area



7.5.5 GENERAL RELATIVITY

ORGANIZATION AND LAYOUT

The spatial organization of the general relativity exhibit area is based around swirling, sloped pathways to suggest a sense of space being flexible rather than rigid. The overall layout curves *with* the outer walls to accentuate the feeling that space warps.

The sloped pathways spiral down—and then back up—around several more central points. These points are accentuated by areas of the smooth ceiling texture surrounded by swirls of the grooved ceiling texture (see **Figure 180**). The behaviour of the architectural elements around these central points illustrates a metaphorical gravitational attraction. The ceiling lights here, too, are grouped above these central points, in the smooth portions of the ceiling.

Counters for exhibit display are attached to the walls between the central points and the sloped pathways. These are attached rather than standalone to maintain the focus on the space as an enclosure rather than on "objects" within the space.

At the southeast side of the general relativity exhibit area, a strip of the ceiling is significantly higher than the average ceiling level; this strip is in line with the stairs connecting this exhibit hall to the next exhibit hall. The raised ceiling strip provides a subtle level of spatial organization to this exhibit area, making navigation clearer for visitors, while avoiding a stricter, more ordered, more hierarchical spatial organization.

Figure 178
Key plan showing location of general relativity exhibit area

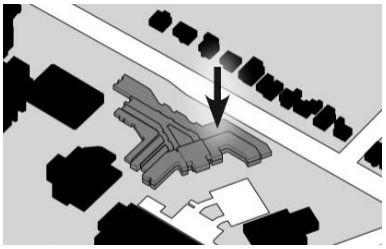


Figure 179
Plan showing the eastern side of the general relativity exhibit area



Figure 180
Reflected ceiling plan showing the general relativity exhibit area



ORBITAL PRECESSION OF MERCURY

The first exhibit area relating to the theory of general relativity is the exhibit area about the orbital precession of Mercury. This exhibit area is located within the lowered floor area encircled by sloped paths, as the architecture here is evocative of the behaviour of orbits.

GRAVITATIONAL LENSING

The other exhibit area in this lowered floor area is about gravitational lensing. Gravitational lensing involves the unusual ability of light to curve around very massive objects, and, along with discrepancies in Mercury's orbit as depicted in the adjacent exhibit area, was used as proof of the theory of general relativity.

To express this in the architecture, two sets of elements are used: one column, located somewhat centrally, and a set of angled spotlights in the ceiling. One spotlight is to one side of the column, and three spotlights are to the opposite side of the column. This arrangement of the column and lights references the multiplication of images that can be produced by gravitational lensing.

Unlike the spotlights used within the special relativity exhibit area to cast multiple shadows from a column, the spotlights here are angled *away* from the column. This both directs light towards the display counters and makes the light act in opposition to how it was established to behave within the previous areas.

Figure 181
Plan showing the orbital precession of Mercury and gravitational lensing exhibit areas



Figure 182
View from adding acceleration exhibit area towards general relativity exhibit area

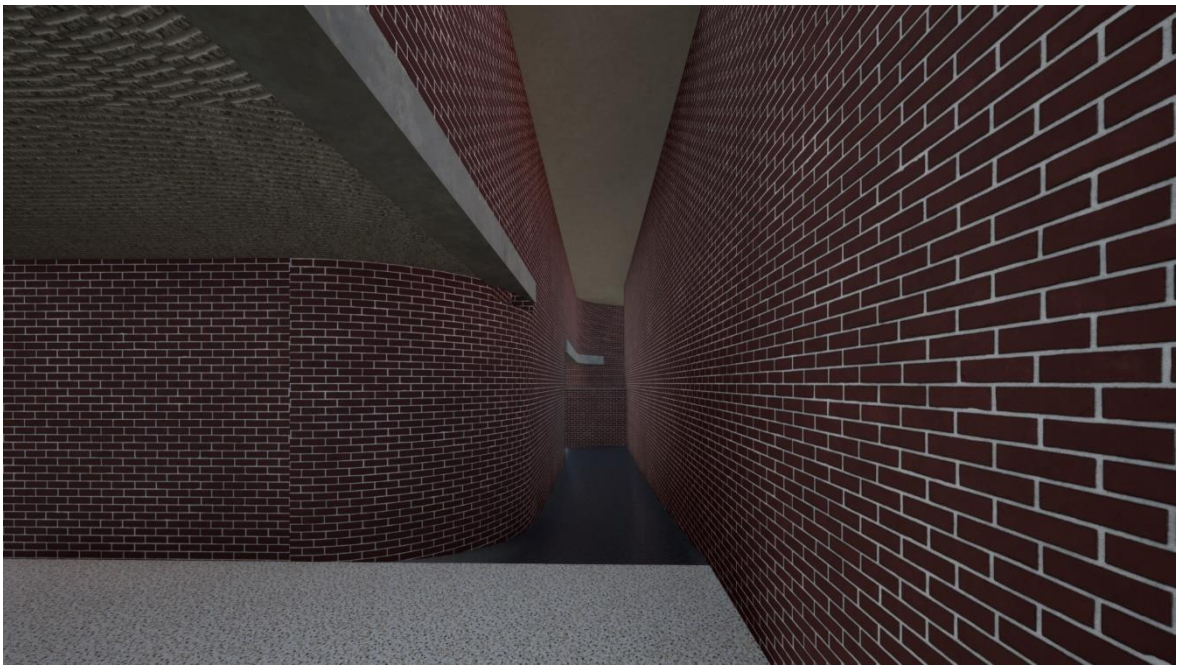


Figure 183
View of the orbital precession of Mercury and gravitational lensing exhibit area



Figure 184
View of the orbital precession of Mercury and gravitational lensing exhibit area



NON-EUCLIDEAN GEOMETRY

The next exhibit area, about non-Euclidean geometry, is located on the higher floor level; non-Euclidean geometry is not inherently related to gravity, and so is not expressed as being pulled into one of the lowered floor areas surrounded by sloping pathways.

Explaining non-Euclidean geometry requires a comparison to Euclidean geometry. The shape of the walls and counters here, then, reflects both Euclidean geometry—the straight sections—and non-Euclidean geometry—the curved section. The curved section in the corner is more sharply curved than other walls in the theory of relativity exhibit hall to draw closer attention to it.

Figure 185
Plan showing the non-Euclidean geometry exhibit area

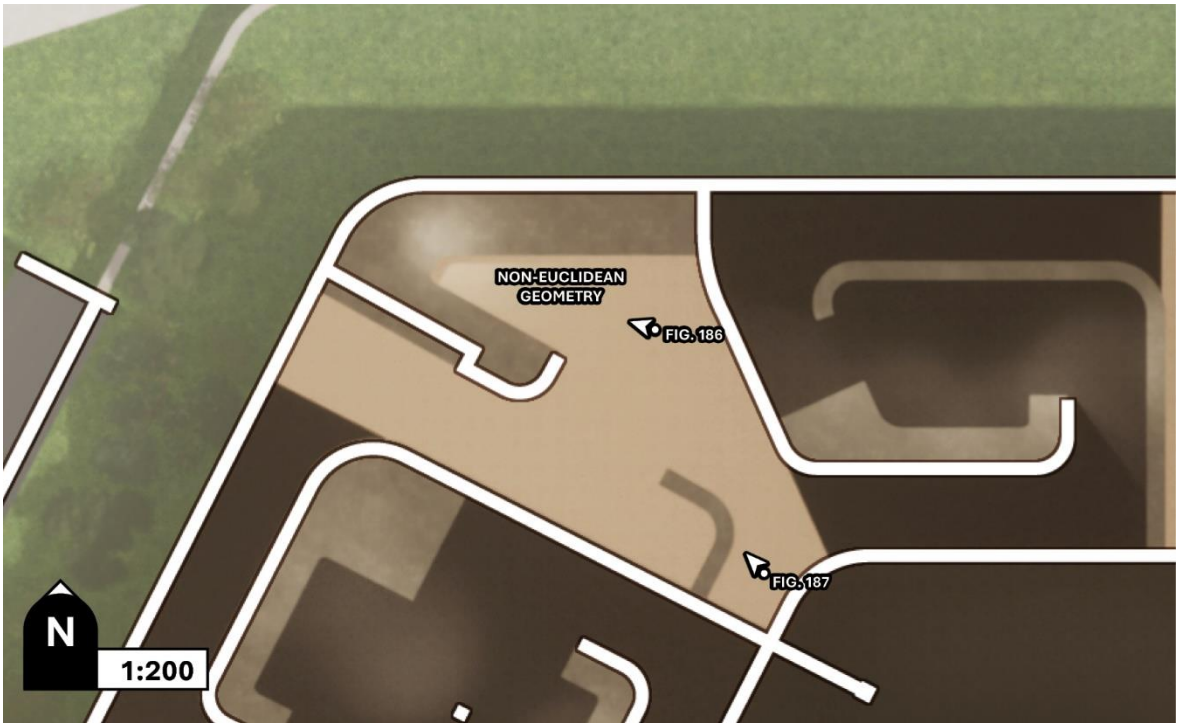


Figure 186
View of the non-Euclidean geometry exhibit area



Figure 187
View of the area to the south of the non-Euclidean geometry exhibit area, towards the west



GRAVITATIONAL TIME DILATION AND REDSHIFT

The next set of exhibit areas, also located in a lowered area surrounded by sloped paths, explain gravitational time dilation and gravitational redshift. While these concepts are similar to their counterparts in special relativity, they are the result of different factors; however, their results are similar so the architectural elements I use here are similar.

The explanations for gravitational time dilation and gravitational redshift that I have used rely on thought experiments involving flashes of light. There are, therefore, multiple ceiling light fixtures arranged in a line to reflect the use of these flashes of light.

In special relativity's exhibit area on time dilation, the overlapping shadows cast by a column were used to suggest the passage of the Sun. Here overlapping cones of light cast by angled spotlights on the ceiling are used instead. To play along with the stretching of time discussed by the exhibit content here, these cones of light are oriented in the same direction, but at different angles (see **Figure 188**).

Figure 188
Section showing the direction of the cones of light within the gravitational time dilation and redshift exhibit area

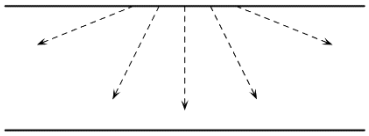


Figure 189
Plan showing the gravitational time dilation and redshift exhibit are



Figure 190
View of the gravitational time dilation and redshift exhibit area



Figure 191
View of the exit from the gravitational time dilation and redshift exhibit area



GRAVITATIONAL WAVES

The next exhibit area explores gravitational waves. Gravitational waves are detected using a type of interferometer, which is the same type of device used in the Michelson-Morley and Kennedy-Thorndike experiments. As such, I use similar architectural language here.

The arms of the interferometer here are represented by an L-shaped counter attached to the partial wall to the east. The point of interference is represented by a column at the corner of the L; this column does not extend fully to the ceiling, just as the column used earlier within the exhibit area for the Michelson-Morley and Kennedy-Thorndike experiments did not extend fully to the ceiling. The column's "incomplete" height helps to distinguish this column from other columns in this exhibit hall, which are used primarily to create shadows.

The elevator up to the loop quantum gravity exhibit hall is located here.

BLACK HOLES AND DARK MATTER

After the gravitational wave exhibit area is the black hole and dark matter exhibit area. The particular theories of dark matter I explore here are related to black holes, and so the architecture here primarily references black holes: the window to the east of the dark matter exhibit area entrance creates a "border" of light before the exhibit area, just as black holes are often surrounded by a halo of light from the black hole's accretion disk[179] just before its event horizon.[180] The stairs that connect the theory of relativity exhibit hall to the loop quantum gravity hall are located here.

The nature of dark matter is unknown, and so the bulk of the exhibit area is hidden from direct view by a wall to provide a sense of mystery.

[179] The event horizon of a black hole is the point beyond which nothing, not even light, can escape the black hole's gravitational pull.

[180] Black holes near stars or large bodies of gas often pull in significant amounts of matter. This matter, before it falls into the black hole, falls into the black hole's orbit and forms a disk. The forces within this disk cause it to become hot and glow.

Figure 192
Plan showing the gravitational wave, black hole, and dark matter exhibit areas

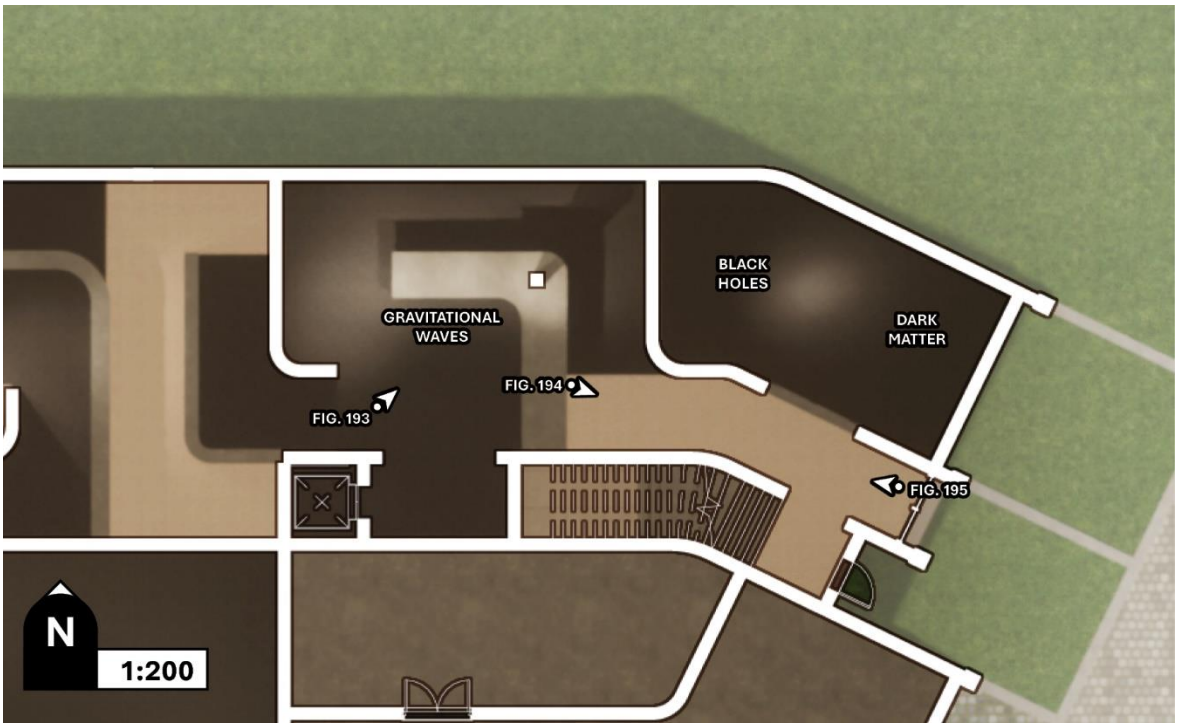


Figure 193
View of the gravitational wave area



Figure 194
View of exit from the gravitational wave exhibit area towards dark matter exhibit area



Figure 195
View of exit stairs from the theory of relativity exhibit hall



7.6 LOOP QUANTUM GRAVITY

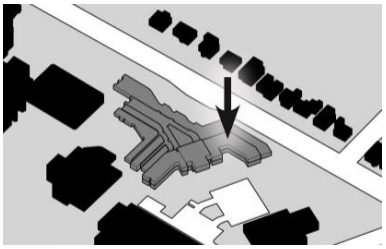


Figure 196
Key plan showing location of loop quantum gravity exhibit hall

ORGANIZATION & LAYOUT

Loop quantum gravity was developed as an extension of the theory of relativity, and so it uses roughly the same architectural forms; for example, there is again a single pathway to suggest a non-hierarchical spatial order. However, loop quantum gravity focuses specifically on the behaviour of space at a very small scale, while the theory of relativity does not, and so there are some differences in the architectural language.

The biggest difference is that loop quantum gravity suggests that space is not continuous, and instead that there exists a smallest possible discrete unit of space. To express this, the loop quantum gravity exhibit hall is divided into discrete areas by walls that *fully* break the space into pieces. Doorways framed in concrete, which contrasts with the colour and texture of the brick walls, bring attention to these spatial divisions.

Figure 197
Plan of loop quantum gravity exhibit hall

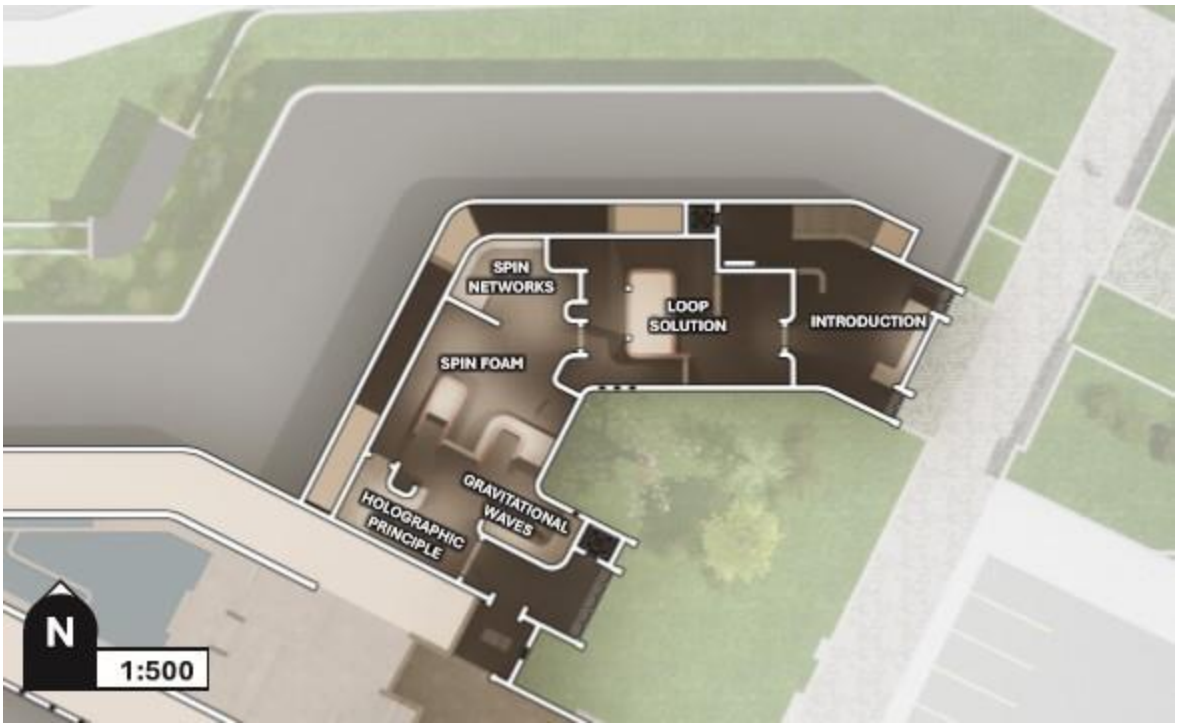


Figure 198
Reflected ceiling plan showing loop quantum gravity exhibit hall



INTRODUCTION

Loop quantum gravity began via the re-formulation of the theory of relativity into the mathematical language of quantum mechanics. As such, the loop quantum gravity exhibit hall begins with an introductory area whose architectural language is more similar to that of the quantum mechanics exhibit hall, before visitors move onto the architectural language of loop quantum gravity.

Following that is a framed doorway that leads to a darker, more mysterious area. The exit to this area uses a framed doorway. The introduction of this new architectural element denotes a change in the behaviour of space.

LOOP SOLUTION

The next exhibit area is fundamental to loop quantum gravity: it explains the loops themselves. Because this area is particularly important, it is more open, particularly in contrast to the previous exhibit area.

The pathway the visitors follow here forms a literal loop, although its two ends do not physically connect. The path simply starts and ends at the same place, at the south side of the exhibit hall just after exiting from the introductory exhibit area. The end of the loop is slightly elevated compared to the start of the loop, and forms a lookout point to draw attention to the point at which the path "closes."

In the centre of the loop is a single standalone framed doorway to draw attention to the division of space. Four lights, arranged in a two-by-two grid, are set into the ceiling within the loop.

Figure 199
Plan showing the introduction and loop solution exhibit areas

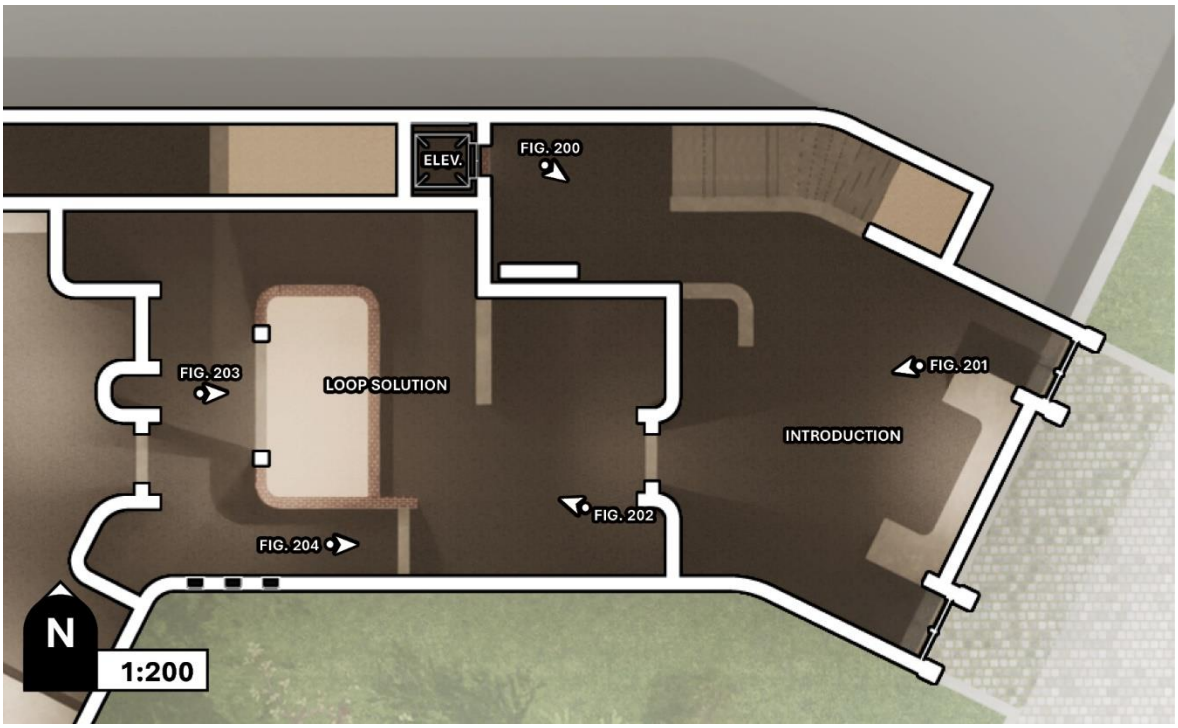


Figure 200
View of entrance to loop quantum gravity exhibit hall from stairs



Figure 201
View of introduction area of the loop quantum gravity exhibit area



Figure 202
View of loop exhibit area



Figure 203
View of loop exhibit area



Figure 204
View of end of the loop in the loop exhibit area



SPIN NETWORKS AND SPIN FOAM

The next exhibit area explores spin networks and spin foam. These are, in the simplest explanation, the combination of multiple loops; in other words, they are the combination of multiple discrete pieces of space.

To express this, multiple framed doorways—or framed walls that resemble closed versions of the framed doorways—enclose the space on the northeast side to give the sense of multiple discrete spaces connecting together.

On the southwest side, similar architectural elements are used, but are instead partial height instead of full height. The space therefore opens up in that direction and provides a view of the layered and partially hidden geometry ahead; this suggests that there is more to discover.

As discussed in Section 6.3.1, I am interpreting loop quantum gravity as implying the use of space itself as a sort of material. To evoke this, the shape of the doorways and walls framing this exhibit area is such that it appears that the two sides of the exhibit area are being pulled apart to create a wider space in between. This is to imply that space, rather than matter, is being stretched. The stretching of space as expressed by the loop quantum gravity hall, which stretches the dimensions of the void space, contrasts with the stretching of space as expressed by the theory of relativity hall, which instead stretches the dimensions and shape of the "matter" elements like walls and columns.

The ceiling features a looping shape similar to that used above the exhibit area about loops. Four lights are again placed in a two-by-two grid on the ceiling, this time to the outside of the loop on the ceiling. The change in placement marks out the two-by-two grid of lights as something to which attention should be paid. The shifting scale of the grid's placement in combination with the grid's organizational consistency references the idea in loop quantum gravity that it is relationships between objects that is most important.

BLACK HOLE EVIDENCE

Loop quantum gravity predicts that black holes will display certain behaviours, and so observation of black holes could provide evidence for or against the theory. This exhibit area is tucked into a corner and not given priority within the architecture, as no such evidence has yet been found.

THE HOLOGRAPHIC PRINCIPLE

The holographic principle states that there is no functional difference between observation of a physical system and observation of the same information from the physical system depicted on a screen. To express this, the exhibit area about the holographic principle is visible in two ways: in the more typical manner by standing next to the display counter, or by looking through a framed portal to the northeast side of the exhibit area.

EXIT

The loop quantum gravity exhibit hall exits through another framed doorway. The elevator from this floor down to the main floor is located here.

Figure 205
Plan showing the southwestern side of the loop quantum gravity exhibit hall

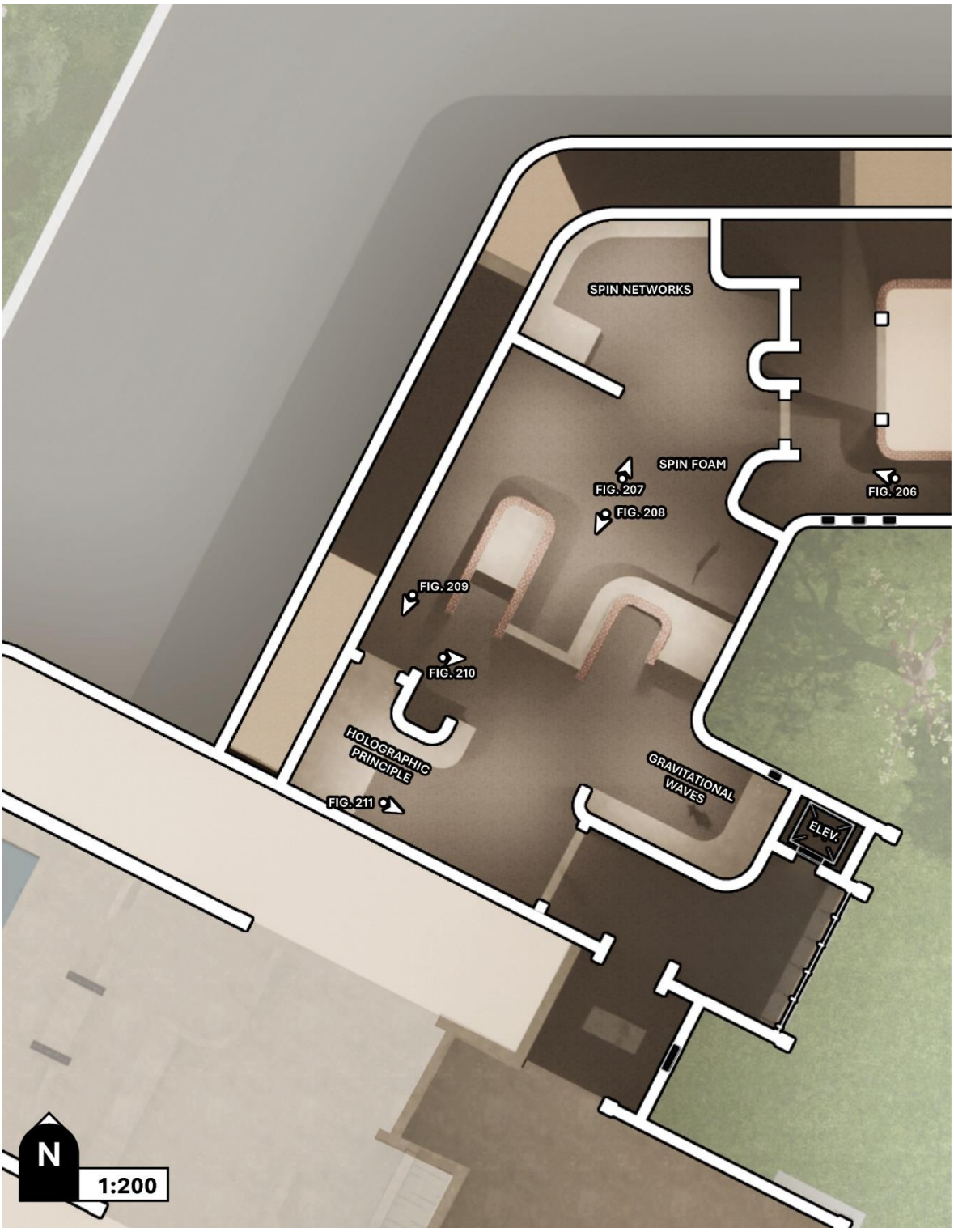


Figure 206
View of entrance to the spin network exhibit area



Figure 207
View of spin network exhibit area



Figure 208
View of spin foam exhibit area



Figure 209
View of holographic principle exhibit area



Figure 210
View of spin foam and black hole evidence exhibit area

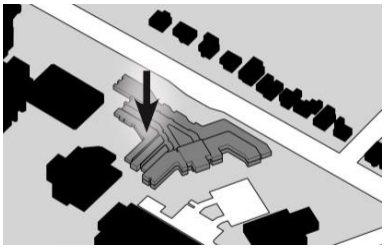


Figure 211
View of exit from loop quantum gravity exhibit hall



7.7 QUANTUM MECHANICS

Figure 212
Key plan showing location of quantum mechanics exhibit hall



7.7.1 ORGANIZATION & LAYOUT

As discussed in Chapter 5, I interpret quantum mechanics as producing a hierarchically ordered model of the universe. To express this architecturally, I take a different approach to the overall layout from that of the theory of relativity exhibit hall. Instead of a single path through the exhibit hall comprised of exhibit areas, there is instead a dominant set of open pathways and a separate, secondary set of exhibit areas (see **Figure 213**). The exhibit areas are demarcated by both a change in floor material and a change in ceiling material and height (see **Figure 214**).

The division of the main circulation from the exhibit areas emphasizes hierarchical order, while the exhibit areas being darker and more secluded gives the sense that the physics being discovered here is hidden rather than obvious. The ceiling height of the main circulation remains level throughout, but the ceiling heights of the three exhibit areas varies: lower for the east and west areas, and higher in the central exhibit area. This variation in ceiling heights offers a subtle impression of uncertainty.

Figure 213
Plan showing quantum mechanics exhibit hall

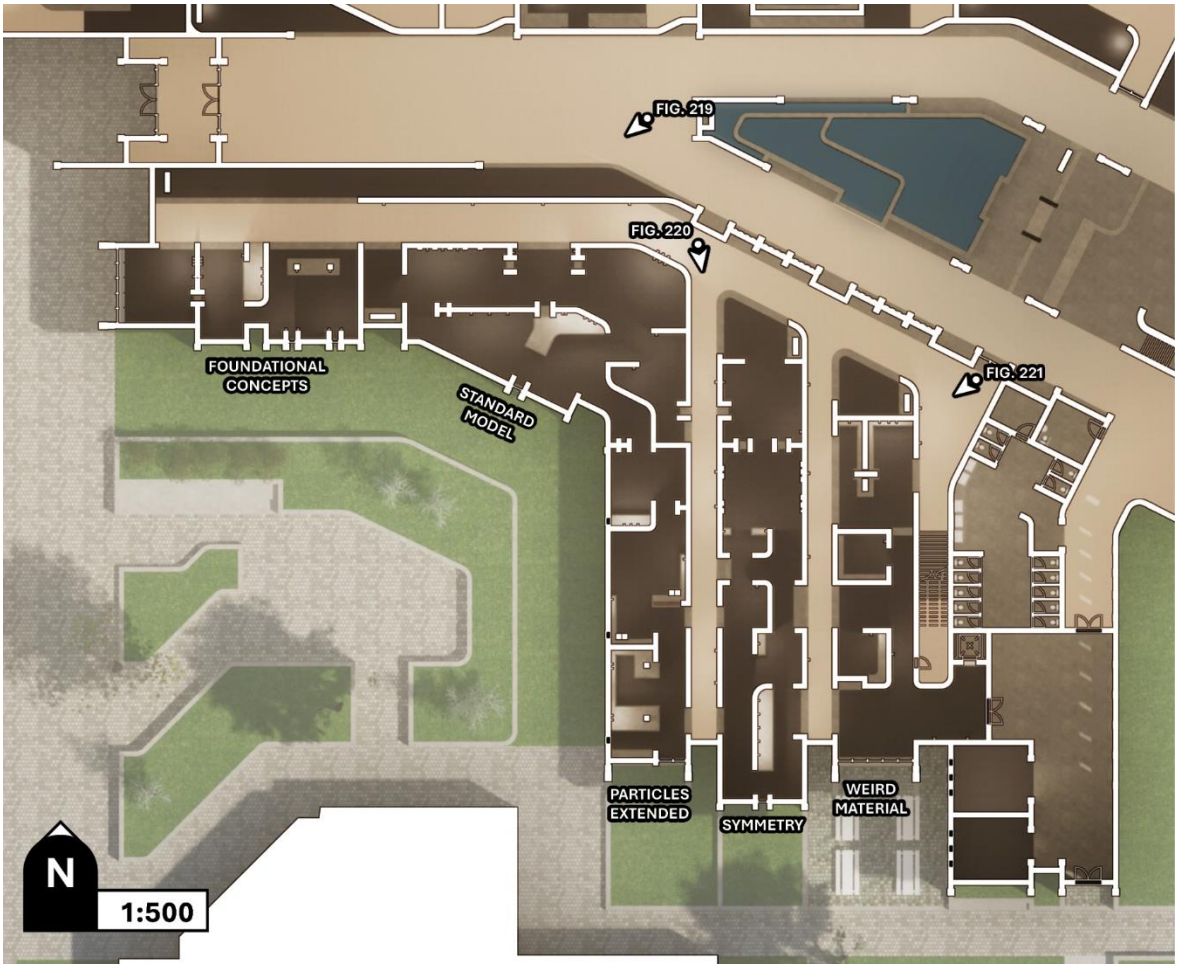


Figure 214
Reflected ceiling plan showing quantum mechanics exhibit hall



Figure 215
Marble tile pattern at Castelvecchio. Photo by Dystopos. License: CC BY-NC 2.0



Figure 216
Quantum mechanics ceiling pattern modules

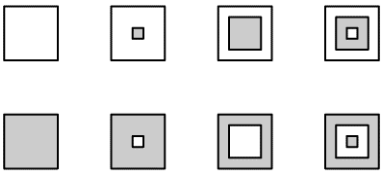
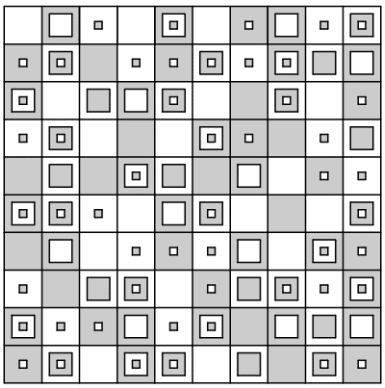


Figure 217
Quantum mechanics ceiling pattern



The ceiling material over the main circulation is the typical smooth plaster. The ceiling texture in the exhibit areas, however, is used to express the texture of the universe that quantum mechanics implies. I take inspiration from two sources: a pattern of non-repeating tiles at Carlo Scarpa's Castelvecchio (see **Figure 215**), and Hilma af Klint's atom drawings.

Scarpa's tile pattern uses two shapes—a square and an L—and two textures of tile—smooth and rough. The two shapes and textures are mixed with changes in the orientation of the tiles and slight variation in colour to produce a pattern that does not repeat, and yet appears strictly ordered; while not inspired by quantum mechanics, Scarpa's tile pattern nevertheless expresses the same combination of uncertainty and hierarchy that we see in quantum mechanics.[181]

I take inspiration from a particular detail in some of af Klint's atom drawings. Within the a 2-by-2 checkerboard that represents the atom in her sketches, some of the squares of the checkerboard, such as in *Atom No. 10* (see **Figure 38** in **Section 5.2**), have the motif of placing a square within a square within a square. While I am unaware of her intent with this motif, to me this is evocative of both the uncertainty of matter in quantum mechanics and the behaviour of matter as both particles and waves.

I combine these two patterns together to form a series of shapes depicting squares within squares (see **Figure 216**) that are then arrayed into a non-repeating pattern (see **Figure 217**). The pattern is formed by smooth and rough textures rather than variations in colour to imply that matter is made up of the same components simply arranged in different configurations.

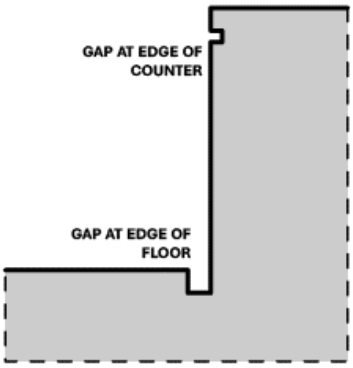
The theory of relativity explores the nature of space and time, while quantum mechanics explores the behaviour of particles within a background space and time. The placement of both full-height and partial-height walls in the quantum mechanics exhibit hall differs from the placement of the walls within the theory of relativity exhibit hall. Instead of walls attaching to the outer walls of the exhibit hall, walls within this exhibit hall primarily stand alone. This placement of the walls downplays the enclosure, and instead places the focus on "objects" within that enclosure, as described in **Section 7.2.1**. Quantum mechanics' disregard for the warping of space is also suggested by the walls throughout the exhibit hall being more generally

[181] Tracey Eve Winton, conversation with author, May 13, 2023.

orthogonal than within the theory of relativity exhibit hall.

The force of gravity is largely ignored by quantum mechanics. The edges of the floor near the walls are detailed with a small gap (see **Figure 218**). The separation of the walls from the floor created by the gap creates the impression that the floor is floating and unaffected by gravity. The edges of the counters, too, feature gaps (see **Figure 218**) to produce a similar effect. The gaps also serve to lengthen the edge conditions, rendering them less strictly defined; this references quantum mechanics' uncertainty. The separation of the architectural elements—floor, wall, and countertop—furthers the sense that these elements are objects.

Figure 218
Section view of gaps at edge of quantum mechanics counters and floors



To further give the impression that gravity is irrelevant here, the light fixtures in the quantum mechanics exhibit hall are designed such that they are attached to the walls with minimal supports so that they appear to be floating. Additionally, these light fixtures radiate in all directions rather than emitting light directionally; I use this to suggest that the lights are more like points in a field than solid objects,

The stairs that lead to the string theory exhibit hall are located to the eastern side of the main circulation; a wider, more open area serves to draw attention to them. The elevator that leads to the string theory exhibit hall is located to the south of the dark matter exhibit area.

Figure 219
View of entrance to quantum mechanics exhibit hall

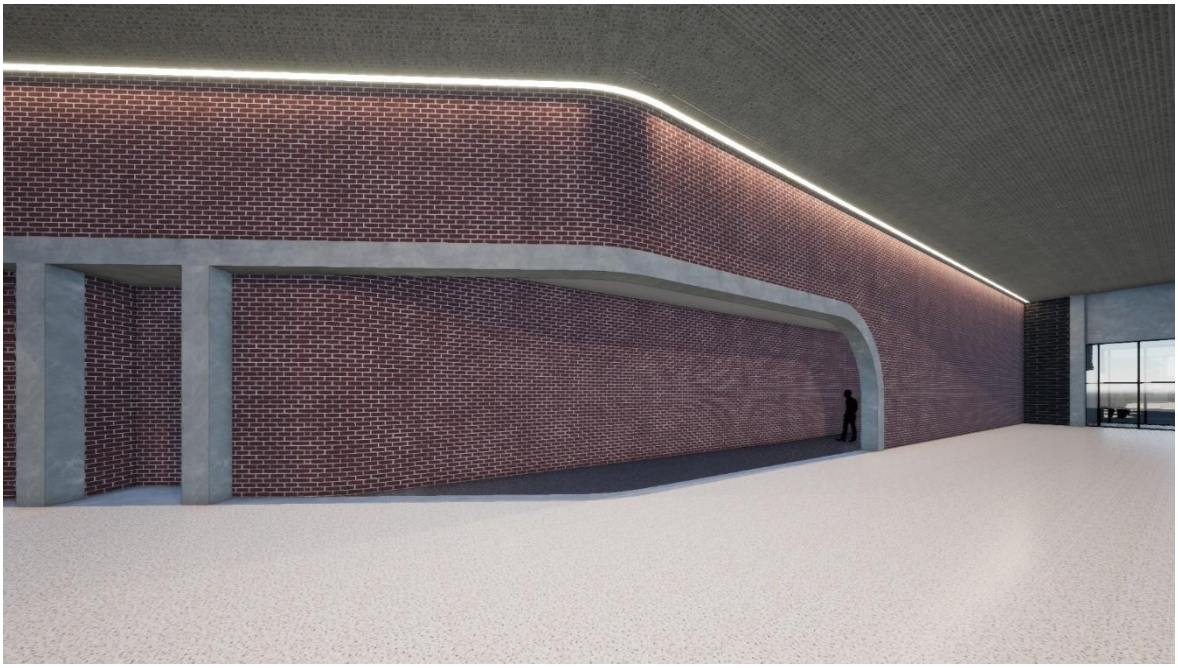


Figure 220
View from north side of quantum mechanics exhibit hall, looking south



Figure 221
View of exit from quantum mechanics exhibit hall, near stairs to string theory exhibit hall



7.7.2 FOUNDATIONAL CONCEPTS

BLACKBODY RADIATION

The first exhibitarea in the quantum mechanics exhibit hall explores blackbody radiation and, particularly, the ultraviolet catastrophe.

As explained in more detail in **Section 5.1.1**, a blackbody can be imagined in a thought experiment as a box that lets in light of all wavelengths, absorbs it all, then emits light back out through a small hole. A broad window to the west of the exhibit area references the idea of capturing a wide spectrum of light, while a much smaller opening on the wall opposite to that window references light being re-emitted through the small hole in the thought experiment.

The east wall of this exhibit area supports four light fixtures. They are arranged as first a set of three light fixtures adjacent to each other, and then a fourth light fixture placed further to their right (see **Figure 223**). The breaking of the fourth light from the order of the first three lights serves to call out that there might be some hidden meaning; this hidden meaning is that the lights form the same pattern as the hydrogen light emission spectrum (see **Figure 224**).

THE PHOTOELECTRIC EFFECT

The next exhibit area explores the photoelectric effect. The small opening from the blackbody radiation exhibit area on this side of the wall references the beam of light that hits the metal plate in the photoelectric effect. Across from the opening is a display counter that then takes a sharp turn to one side; this evokes the sense of the light bouncing off of the surface it impacts.

The four light fixtures in the blackbody radiation exhibit area are reflected to the other side of the wall. These lights reference the existence of the inverse of emission spectra—absorption spectra. The behaviour of the absorption and emission of light by particles is a key principle of the photoelectric effect.

THE DOUBLE-SLIT EXPERIMENT

The next exhibit area explains the double-slit experiment. The two windows in the south wall directly reference the two slits used in the experiment, and the columns in the centre of the exhibit reference points of interference, just as within the Michelson-Morley, Kennedy-Thorndike, and gravitational wave exhibit areas within the theory of relativity exhibit hall.

Figure 222
Key plan showing location of foundational concepts of quantum mechanics exhibit area

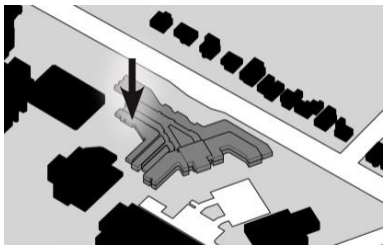


Figure 223
View of the pattern of lights used within the blackbody radiation exhibit

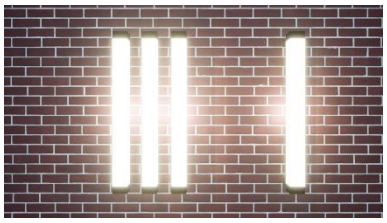


Figure 224
Hydrogen emission spectrum in the visible wavelengths. Image by Adrignola. License: CC0 1.0



Figure 225
Plan showing foundational concepts in quantum mechanics exhibit hall

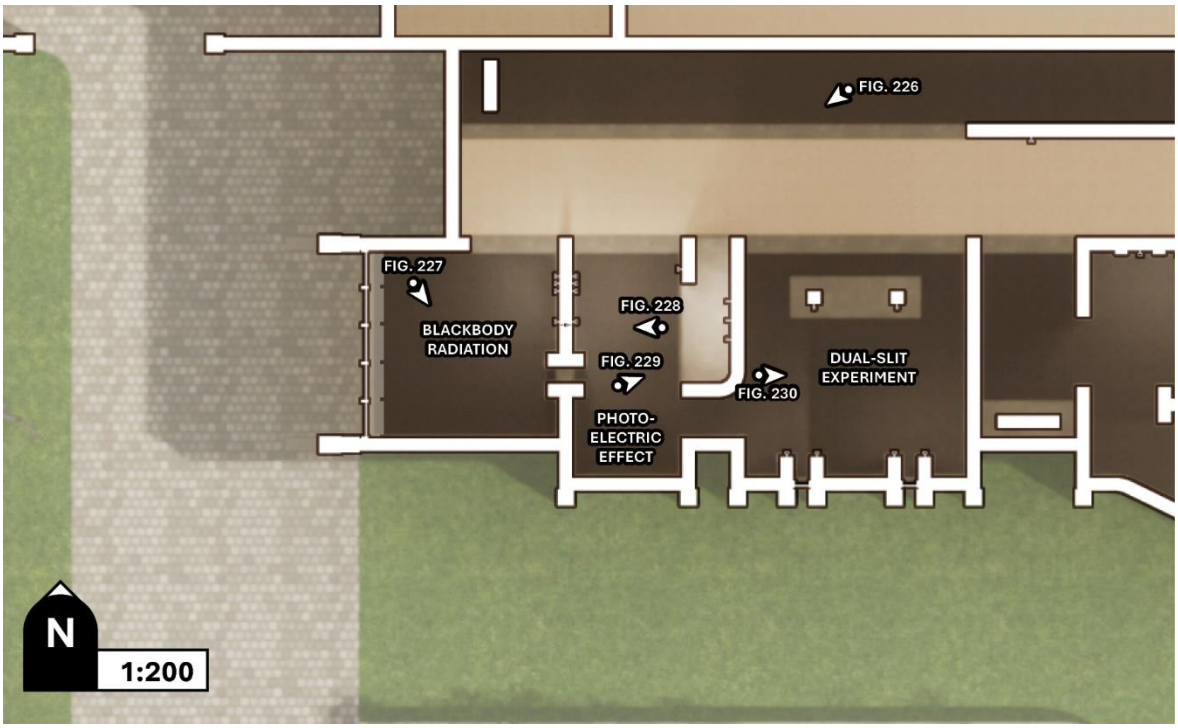


Figure 226
View of foundational concepts in quantum mechanics exhibit hall



Figure 227
View of blackbody radiation exhibit area

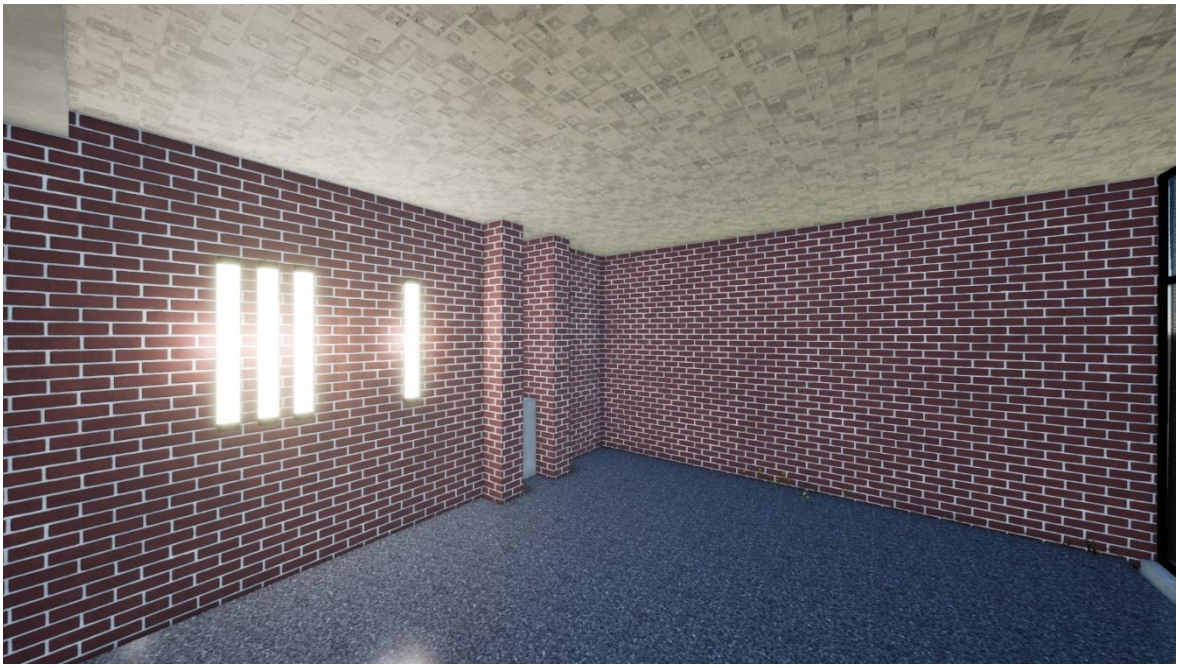


Figure 228
View of the wall of the photoelectric effect exhibit area adjacent to the blackbody radiation exhibit area

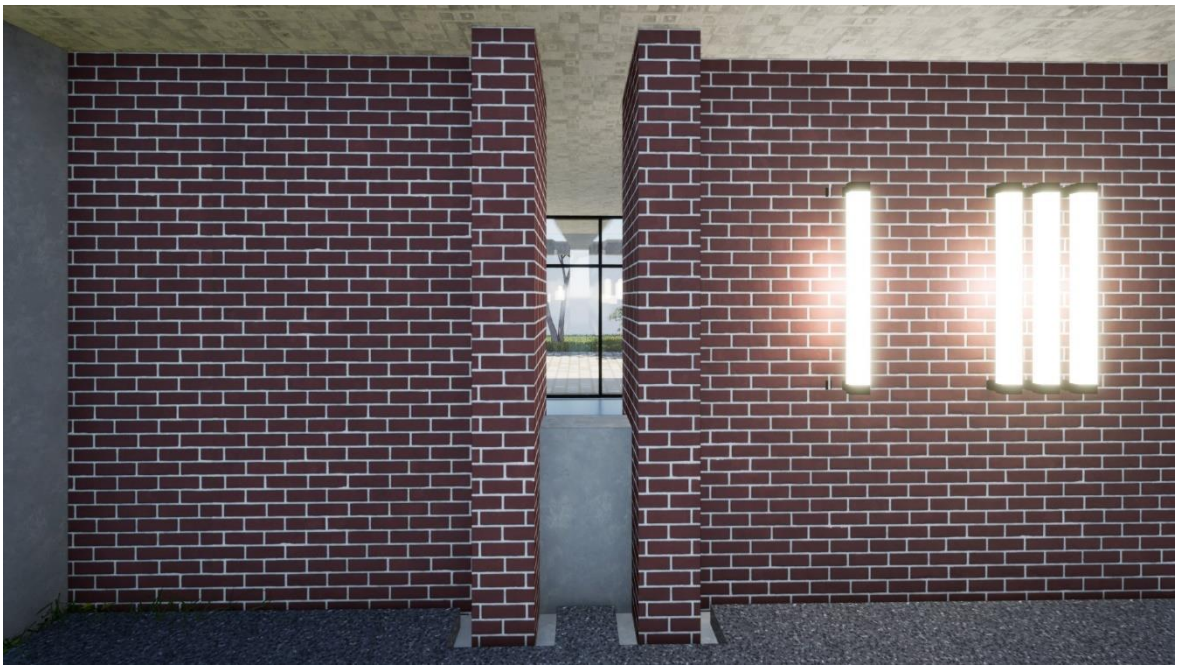


Figure 229
View of photoelectric effect exhibit area

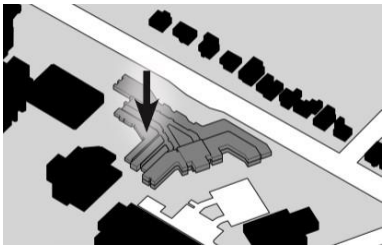


Figure 230
View of double slit experiment exhibit area



7.7.3 STANDARD MODEL

Figure 231
Key plan showing location of the Standard Model exhibit area



The next set of exhibit areas explores details about the Standard Model of quantum mechanics. The Standard Model is incredibly important to the theory of quantum mechanics as a whole, and so this exhibit area begins with a larger, more noticeable piece of signage at its western entrance. The Standard Model also represents a change in thought about the nature of matter, and so it occupies the literal turning point at the corner of the quantum mechanics exhibit hall.

FUNDAMENTAL FORCES

The first exhibit area within the Standard Model area deals with the fundamental forces. Quantum mechanics explains the behaviour of three of the four fundamental forces. Solving gravity's absence from quantum mechanics is integral to the search for a unified theory of physics, and so I want to call out its absence here in the architecture even if the exhibit area itself does not explore it. To do this, I place four columns on the walls to create four gaps. In three of the gaps, there are light fixtures on the wall—referencing electromagnetism, the strong nuclear force, and the weak nuclear force—and then the fourth gap has no light fixture and is marked by darker, heavier brick to reference the absence of gravity.

BARYONS

To the south of the fundamental forces exhibit area is the exhibit area about baryons. The behaviour of the fundamental forces and all types of fermion, including baryons, are interlinked; a small opening between these two exhibit areas represents this interconnection more explicitly.

QUARKS

To the southeast of the main fermion exhibit area is the quark exhibit area. While quarks make up baryons, their importance to quantum mechanics warrants more specific explanation and a larger space. The light fixtures here come in a pair of two and a set of three; this references the fact that quarks always come in pairs or triplets.

LEPTONS

Directly to the east of the fundamental forces exhibit area is the lepton exhibit area. Leptons are particles with little mass, and so this exhibit area is both smaller and more exposed to reduce the sense of weight produced by enclosing walls.

Leptons are a type of fermion, just as quarks and other baryons are. As such, there is a small opening to the south connecting the lepton exhibit area to the baryon and quark exhibit area.

BOSONS

Bosons are the particles that transfer forces between other particles. The boson exhibit area therefore connects visually to the fundamental forces exhibit area via two wall openings along the same axis, on both the west and east sides of the lepton exhibit area.

HIGGS BOSON & FIELD

The Higgs boson, while also a boson, is particularly important to quantum mechanics as it relates to how the other particles have mass. As such, I have given it a larger exhibit area next to the main boson exhibit.

The method by which the Higgs field gives particles mass relates to the concept of symmetry in quantum mechanics. The wall to the southeast of the Higgs exhibit area, then, features an opening paired with an identical opening across the main circulation path that connects the Higgs exhibit area visually to the exhibits about symmetry.

The two walls to the north side of the Higgs exhibit area are parallel, and appear as if they might have been a single wall that was broken apart (see **Figure 239**); a light on the end of each wall, visible from inside the Higgs exhibit area, emphasizes this. This implied breakage refers to the breaking of weak symmetry related to the Higgs field.

Figure 232
Plan showing Standard Model exhibit area

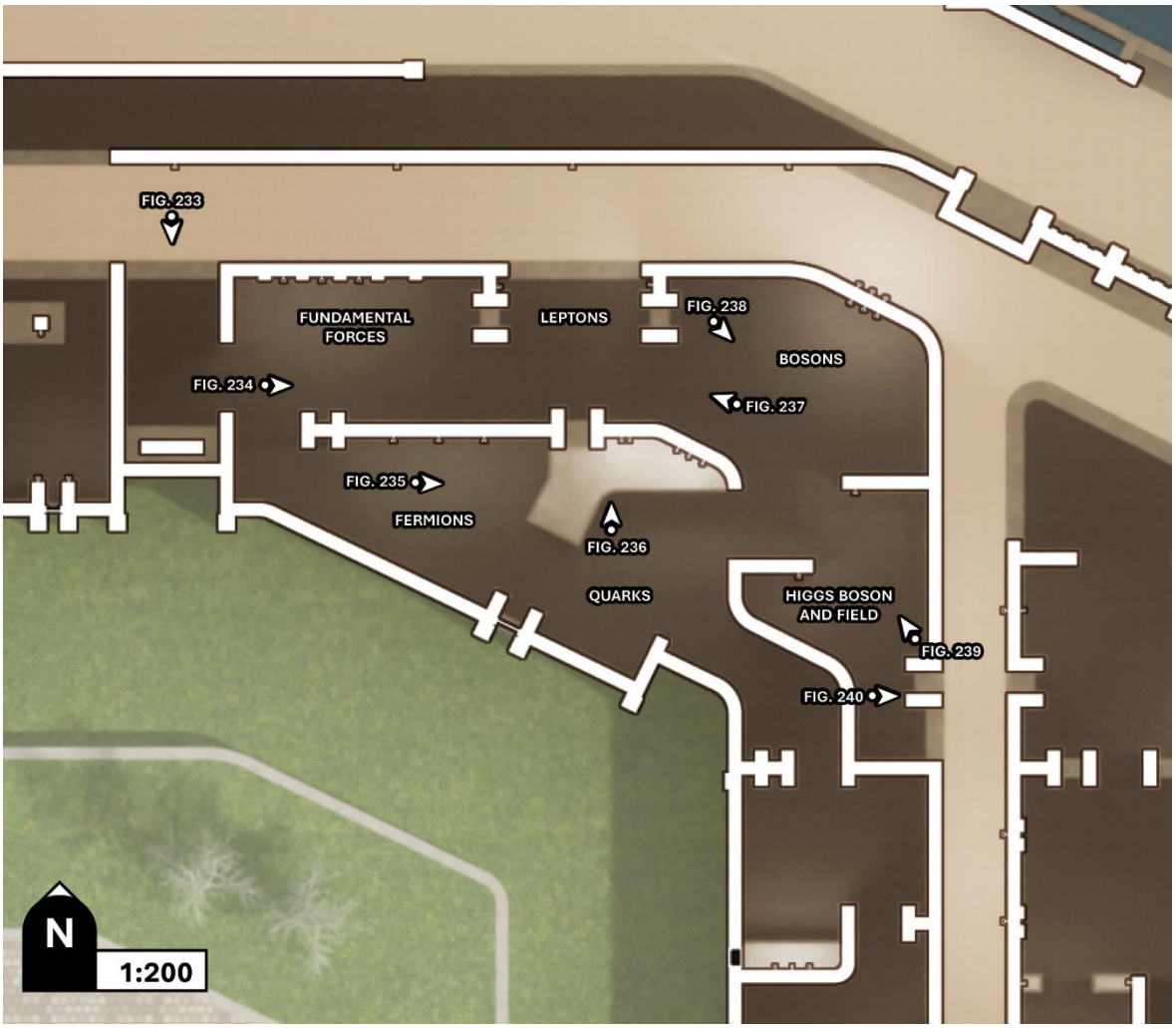


Figure 233
View of the entrance to the Standard Model exhibit areas



Figure 234
View of fundamental forces exhibit area, from west side looking east

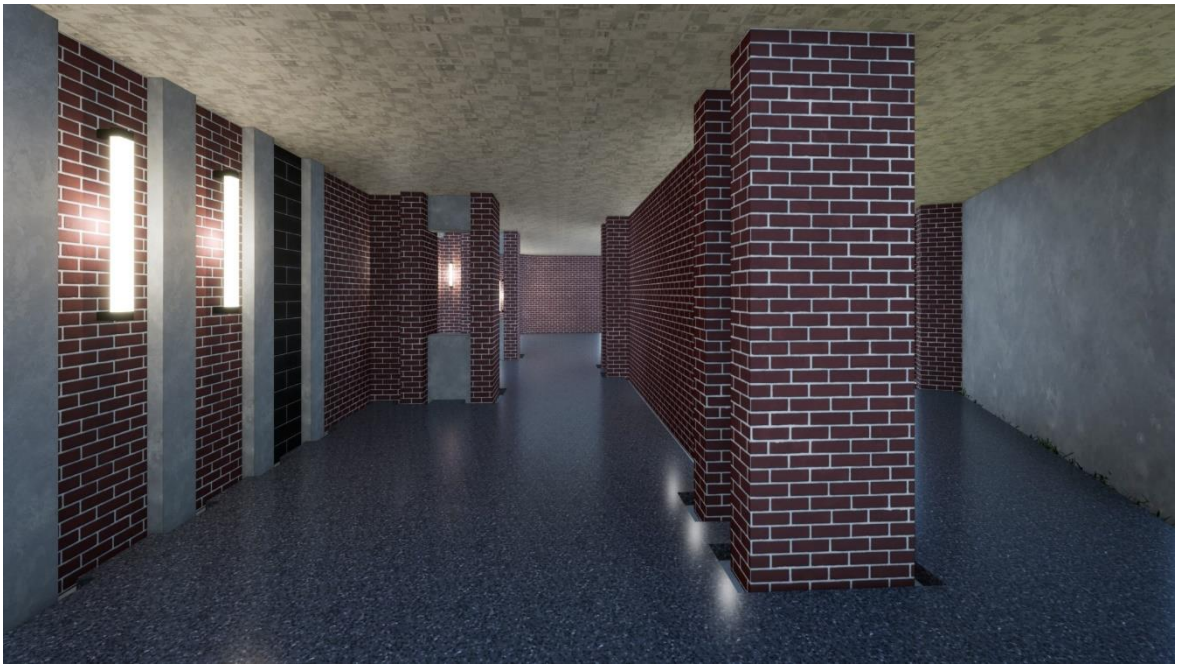


Figure 235
View of fermion exhibit area, looking towards quark exhibit area



Figure 236
View of wall on north side of quark exhibit area



Figure 237
View of the lepton exhibit area, from the boson exhibit area

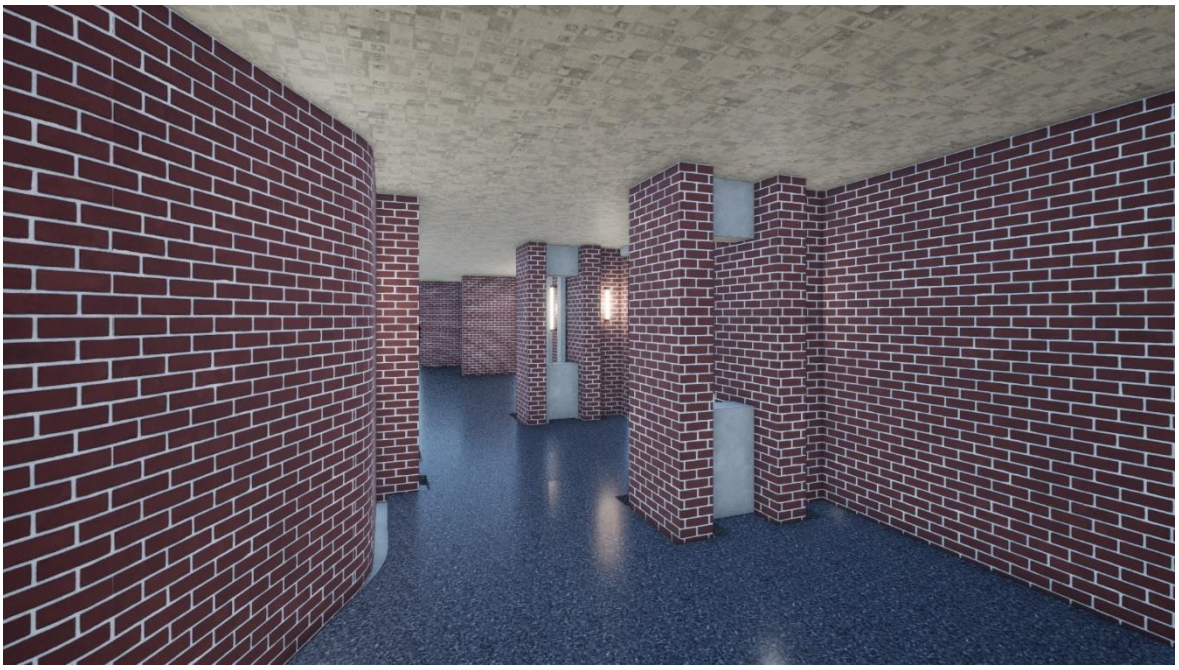


Figure 238
View from boson exhibit area, looking towards Higgs exhibit area

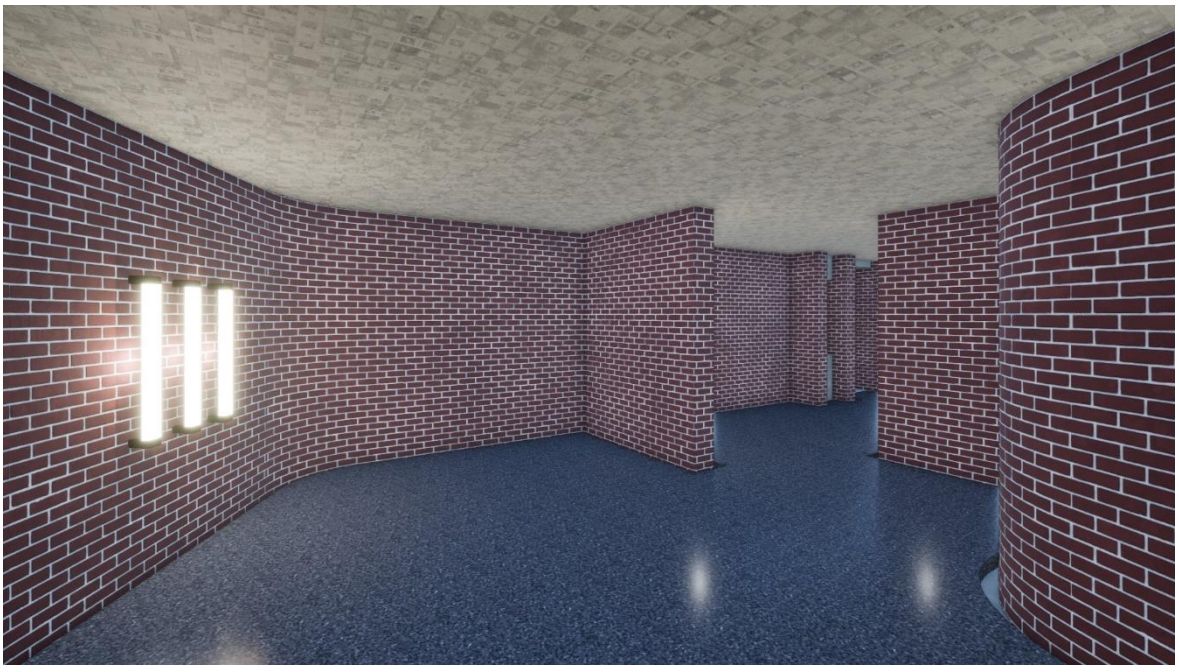


Figure 239
View of Higgs exhibit area, from south looking northwest

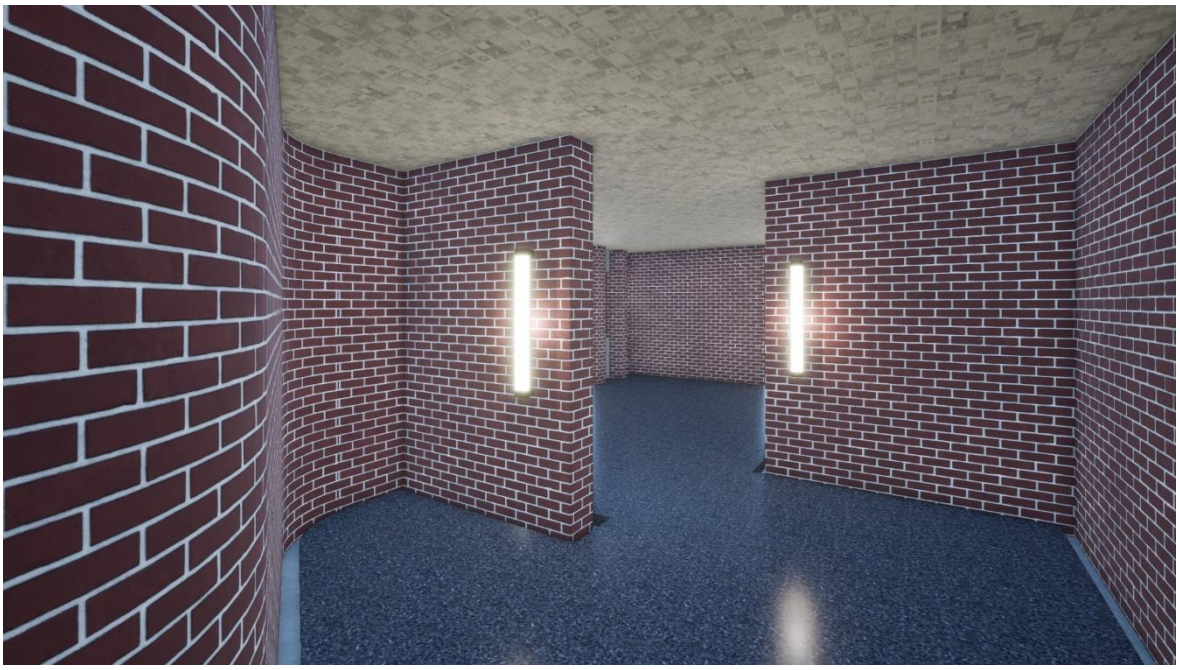


Figure 240
View from Higgs exhibit area looking towards symmetry exhibit area through opening in wall



7.7.4 PARTICLES EXTENDED

QUANTUM CHROMODYNAMICS

The first exhibit area to the south of the Standard model exhibit area explores quantum chromodynamics. Quantum chromodynamics involves the behaviour of a particular quark property, referred to as "colour," which comes in variants referred to as red, green, and blue.

As discussed in **Section 5.1.3**, combinations of quarks must result in a neutral white colour. For a set of three quarks, then, there must be one red, one green, and one blue quark. To represent further investigation of these three colours of quark, the entrance to the quantum chromodynamics exhibit area features a wall split into three with the addition of two perpendicular shorter walls. Two portions of this split wall remain solid, while the third portion is open and acts as a doorway.

As a reference to the use of terms relating to colour and light in quantum chromodynamics, there is a window to let light in on the west wall. Near the window are three lights, again to refer to the three colours of quantum chromodynamics.

PREON MODELS

The next exhibit area explores preon models. As discussed in **Section 5.1.3**, preons are hypothetical particles, pairs of which make up quarks. The entrance from quantum chromodynamics to this exhibit area uses the same architectural elements as the transition from the Standard Model to the quantum chromodynamics exhibit areas did, but the connecting wall is split into two rather than three to represent the two preons in a quark.

Two sets of paired columns in this exhibit area emphasize the idea in quantum mechanics that particles often come as pairs. A single light is located on the wall next to each column.

ENTANGLEMENT

The final exhibit area on the western side of the quantum mechanics exhibit hall explores quantum entanglement. To express the idea of entanglement, two columns are located separate from each other but are implied to be connected by a counter than surrounds them both. A pair of lights is located next to each pair of columns.

Figure 241
Key plan showing location of the extended particles exhibit area

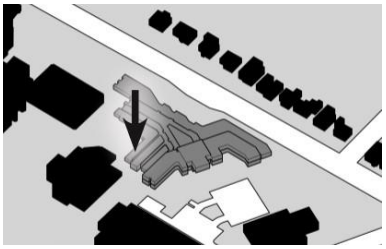
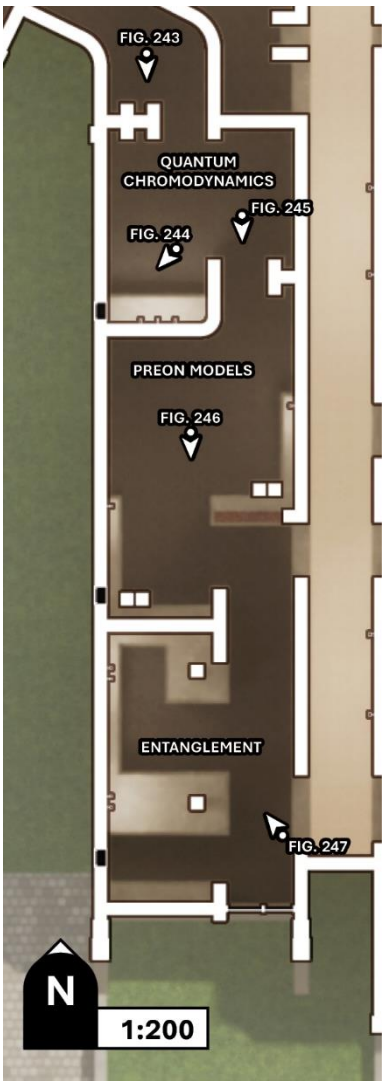


Figure 242
Plan showing the southwestern exhibit area of the quantum mechanics exhibit hall



The number of lights and the number of columns in the preon model exhibit area are reversed in the entanglement exhibit area to reference the idea of symmetry in quantum mechanics.

Figure 243
View of exit from quark exhibit area to quantum chromodynamics exhibit area



Figure 244
View of counter in quantum chromodynamics exhibit area



Figure 245
View of exit from quantum chromodynamics exhibit area to preon model exhibit area



Figure 246
View of preon model exhibit area, from north looking south



Figure 247
View of entanglement exhibit area, from south looking north



7.7.5 SYMMETRIES

ORGANIZATION AND LAYOUT

The central exhibit area within the quantum mechanics exhibit hall deals with theories of symmetry. While the quantum mechanical definition of symmetry is not precisely the same as the geometrical definition of symmetry, I believe that geometrical symmetry within the architectural forms is an appropriate expression for symmetry within quantum mechanics. Both definitions refer to the idea that one thing can stand in for another without changing its behaviour.

To emphasize symmetry, this exhibit area is located in the central north-south strip of the quantum mechanics exhibit hall. To further the symmetry, there is a dividing axis oriented north-south down the centre of this strip. Walls and display counters are placed on either side of this axis.

THE GAUGE PRINCIPLE

The gauge principle, which suggests that a particle within some particle interaction can be replaced by another, distinct type of particle without changing the behaviour of the interaction, is fundamental to theories in quantum mechanics that deal with symmetry. The gauge principle exhibit area, therefore, acts as an introductory area for the two following exhibit areas. Looking south from the gauge principle exhibit area, visitors can see that the next two exhibit areas are quasi-symmetrical. Two window-like breaks in the wall emphasize the connection between the gauge principle and the two types of symmetry the following two exhibit areas explore.

Figure 248
Key plan showing location of the symmetry exhibit area

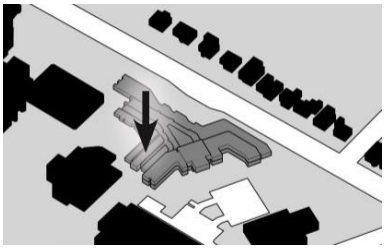
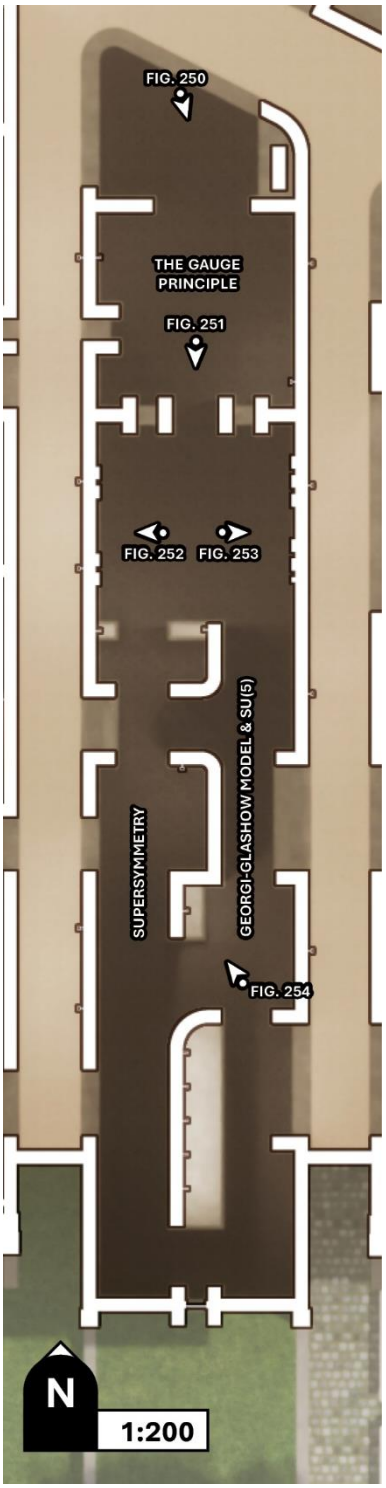


Figure 249
Plan showing the central exhibit area of the quantum mechanics exhibit hall



SUPERSYMMETRY

The exhibit area on the western side explores supersymmetry, which is the theory that deals with symmetry between fermions, which are matter particles, and bosons, which are force-carrying particles. To express this symmetry, on the wall near the beginning of the exhibit area is a pair of concrete columns followed by a concrete column paired with a brick column. Similarly to how Grenville Davey's sculptures inspired by string theory (see **Section 6.4.2**) first establish an expectation for the relationship between a pair of objects, and then call attention to a missing fourth object when a third appears alone, the first pair of columns establishes an expectation which is then broken by one of the columns in the second pair being made of a different material. The use of a different material for the final column suggests that it is a fundamentally different substance.

THE GEORGI-GLASHOW MODEL & SU(5)

The exhibit area on the eastern side explores the Georgi-Glashow Model and SU(5). These theories deal with symmetry between quarks and leptons. Quarks are the smaller particles that make up heavier particles like neutrons and protons, and leptons are minuscule particles that can exist individually.

Like in the supersymmetry exhibit area, here I use on the eastern wall a set of regular concrete columns —three, this time, to reference quarks typically coming together in threes—to establish an expectation. This set of three columns is followed by a set of two columns of a similar size and a single thinner column, all made of concrete. The columns all being the same material suggest that they are made of the same substance; the changed dimensions of the final column suggest instead a variation in scale.

Figure 250
View of entrance to symmetry exhibit area

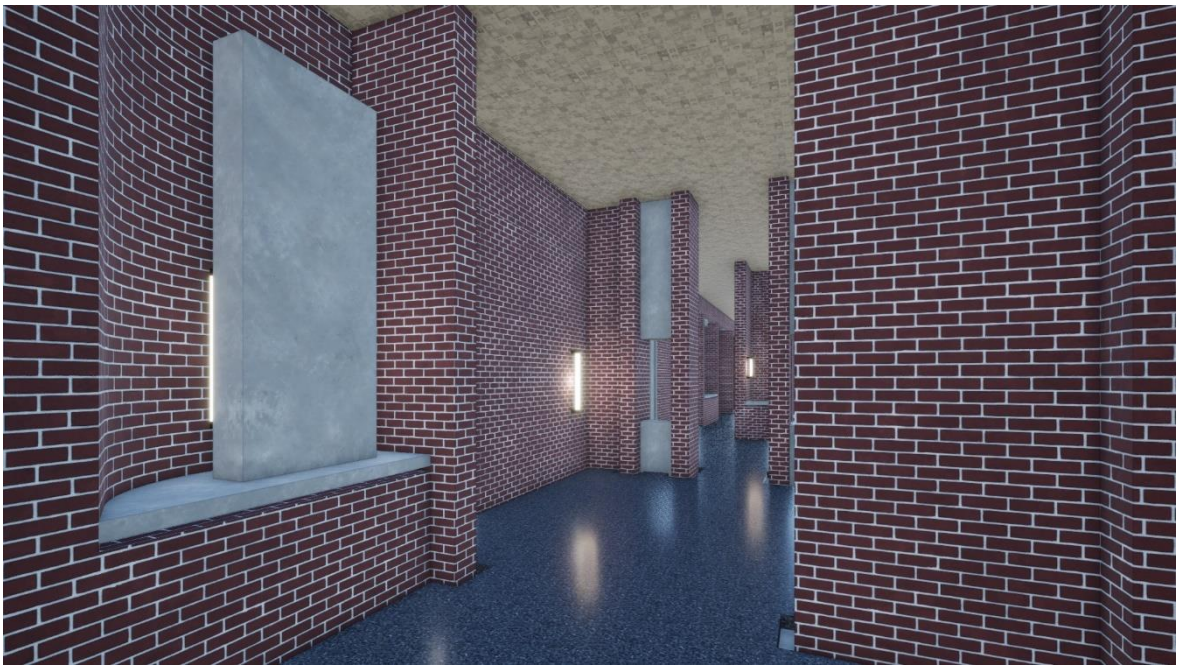


Figure 251
View looking south from the gauge principle exhibit hall

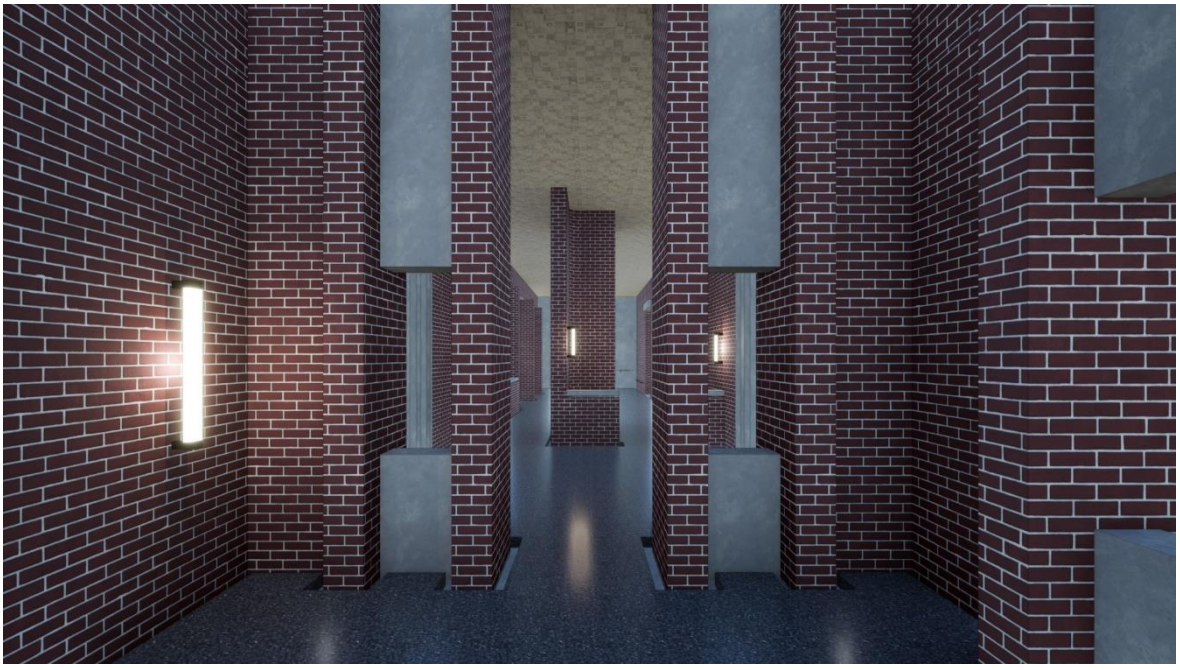


Figure 252
View of the columns on the western wall to the north of the symmetry exhibit areas

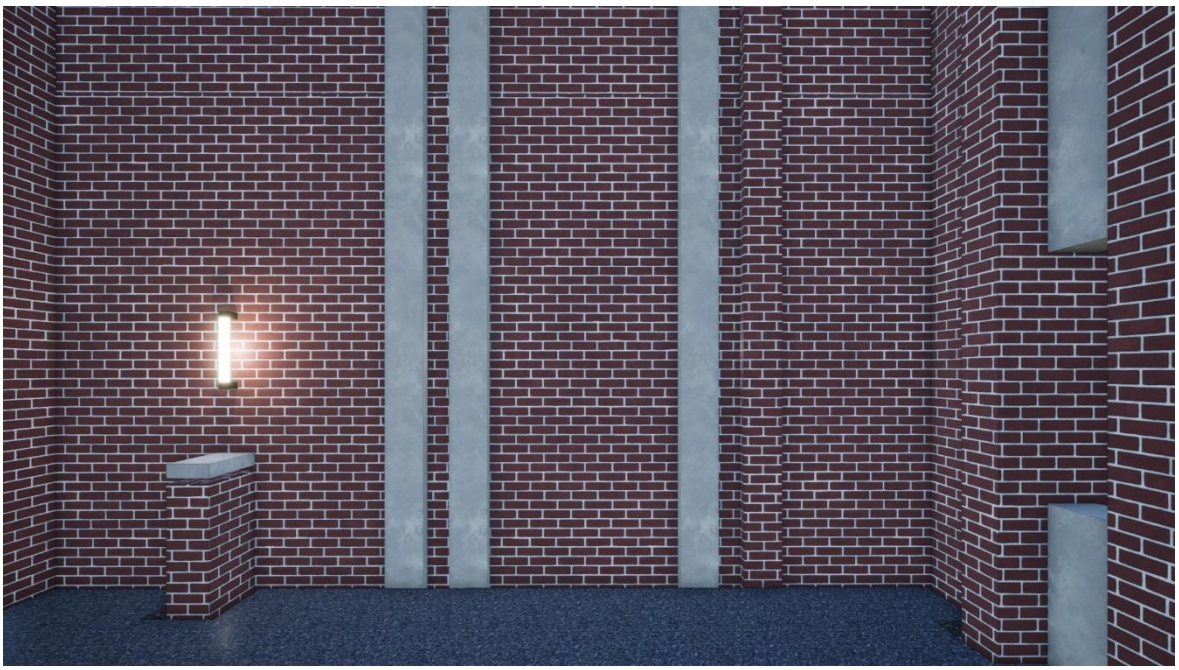


Figure 253
View of the columns on the eastern wall to the north of the symmetry exhibit areas

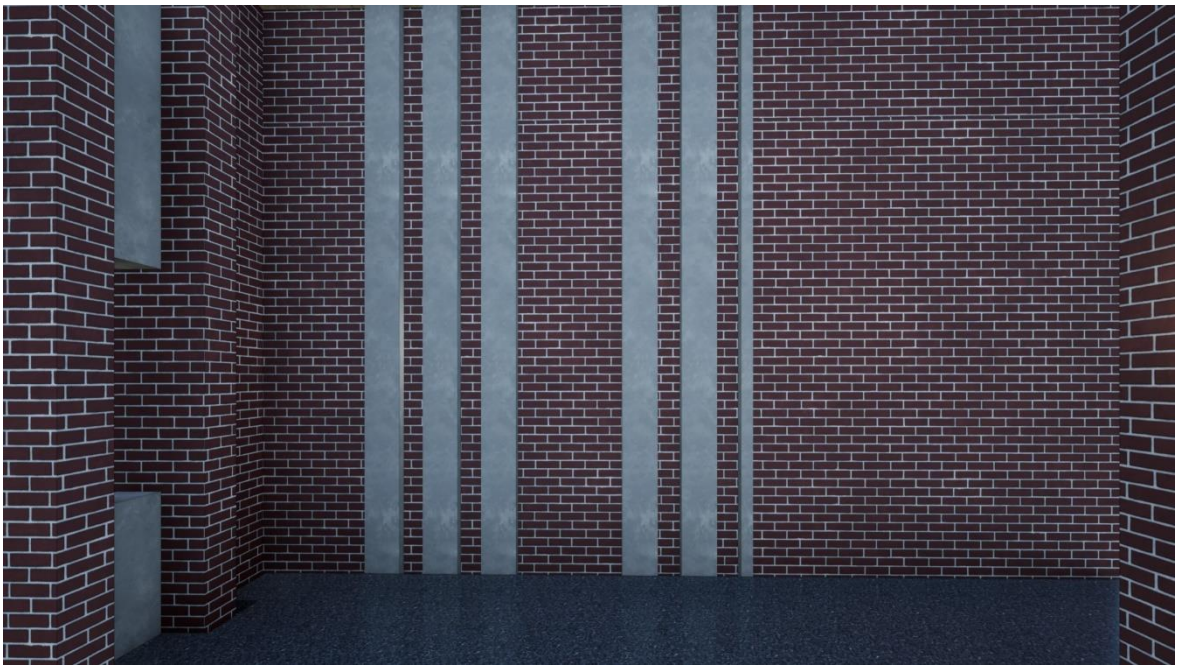
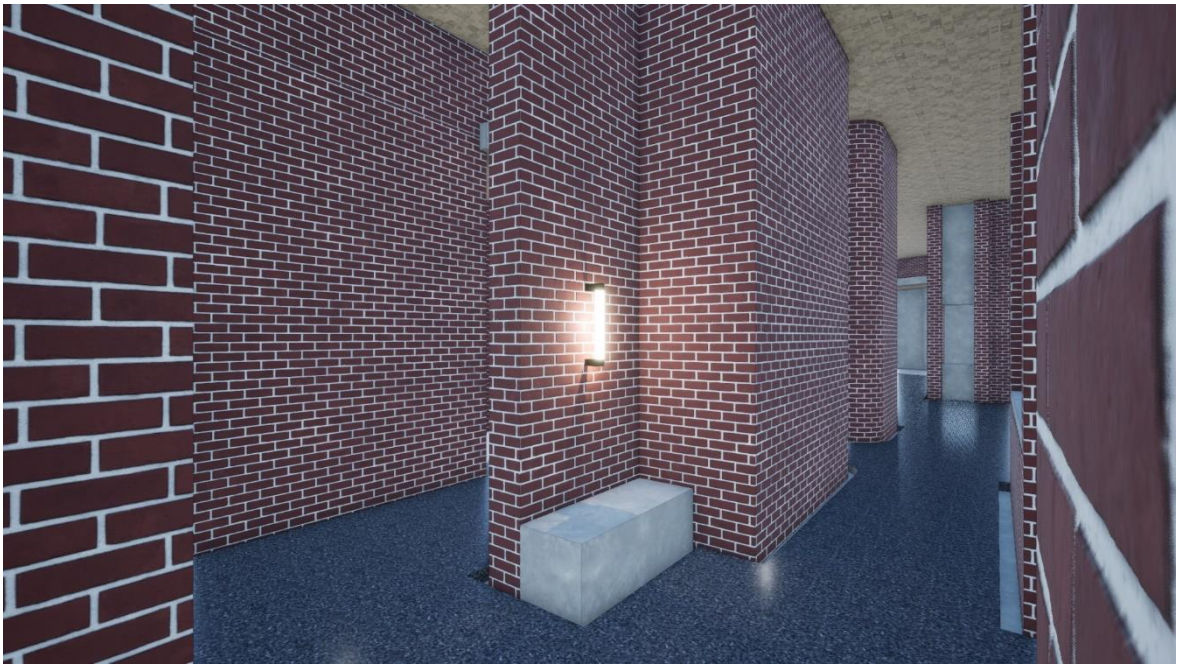


Figure 254
View of the Georgi-Glashow Model and SU(5) exhibit area



7.7.6 WEIRD MATERIAL

ANTIMATTER

The first exhibit area in the eastern area explores antimatter. The behaviour of antimatter expressed by the architecture is matter-antimatter annihilation. Two walls approach each other and are then interrupted by another, perpendicular wall that acts as a point of "collision" between the two walls. One of the two colliding walls is significantly longer than the other, referencing the predominance of matter over antimatter in the observed universe.

DARK MATTER THEORIES

The final exhibit area in the quantum mechanics exhibit hall explores theories of dark matter. Dark matter is impossible to see with light and all theories of what it could be remain hypothetical, and so the exhibit areas are located within smaller, darker rooms that cannot be seen directly from the main circulation. The light fixtures are located so that they are not directly visible when approaching the dark matter exhibit area, but the hints of light that *can* be seen imply their existence.

Figure 255
Key plan showing location of the weird material exhibit area

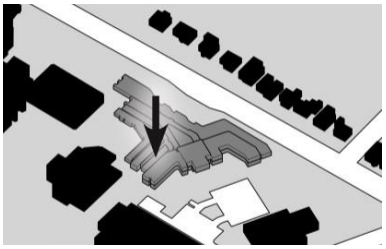


Figure 256
Plan showing the eastern exhibit area of the quantum mechanics exhibit hall

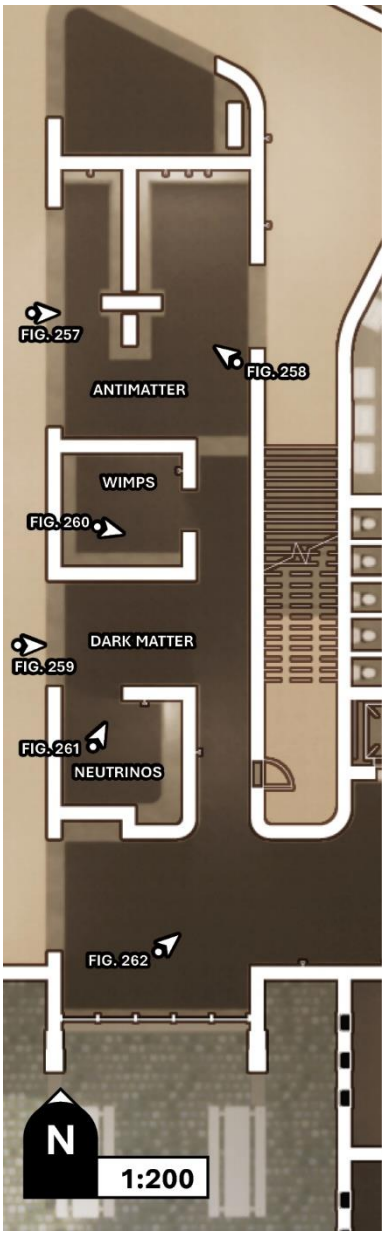


Figure 257
View of antimatter exhibit area



Figure 258
View of antimatter exhibit area

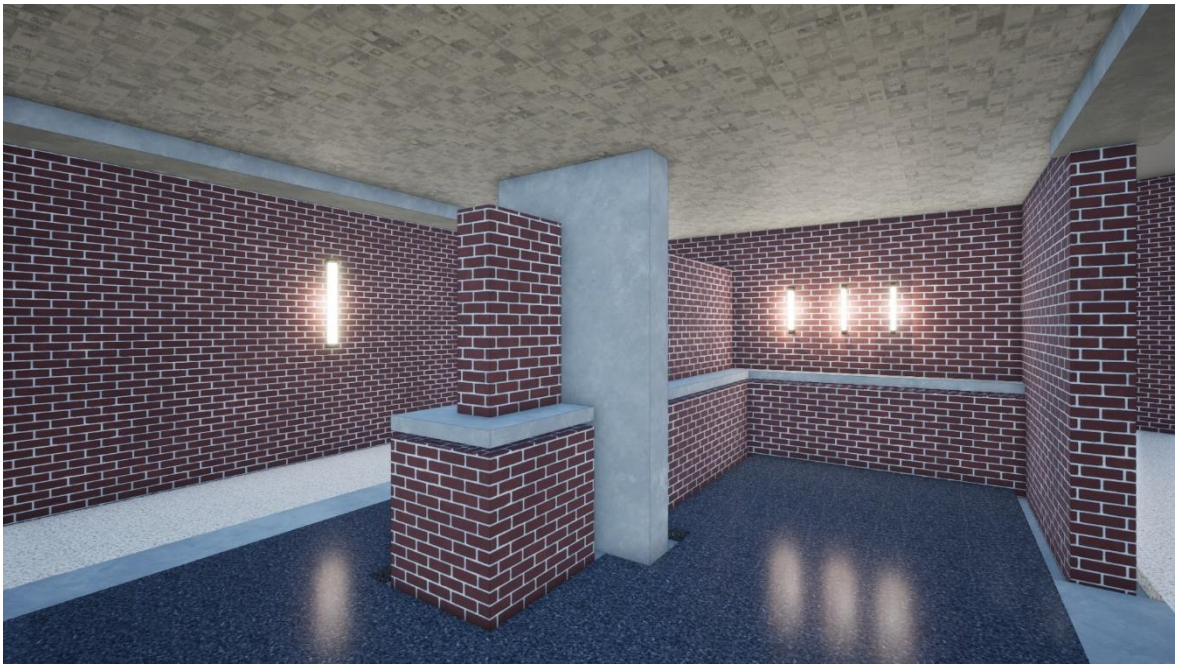


Figure 259
View of entrance to dark matter exhibit area

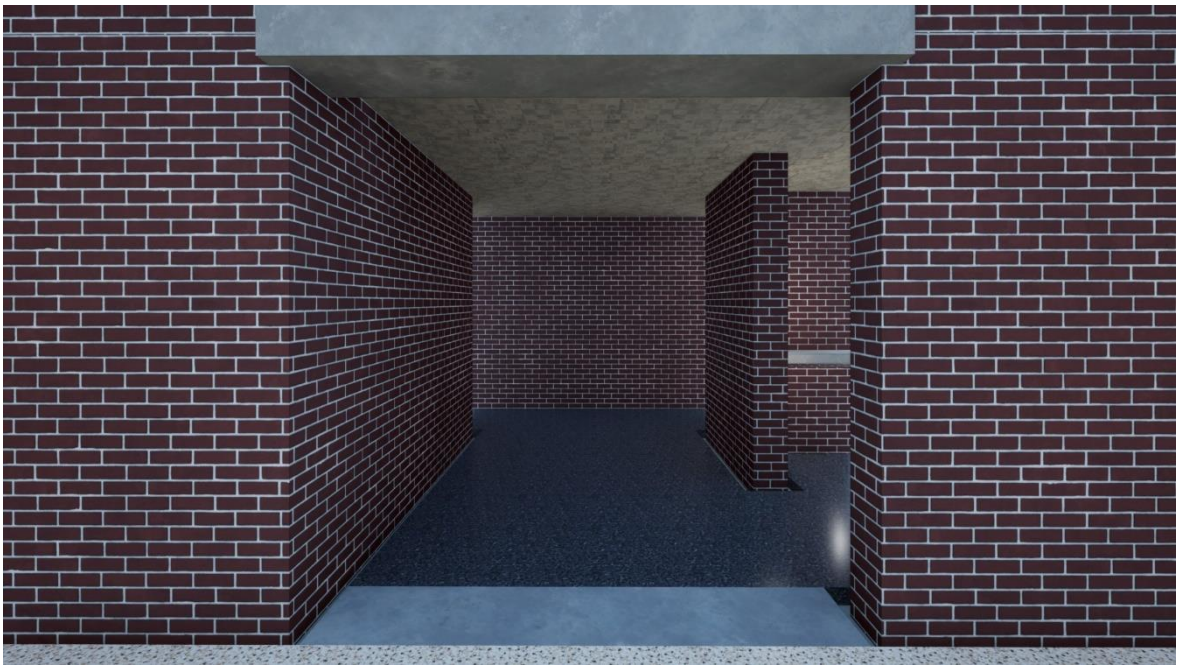


Figure 260
View of WIMP exhibit area

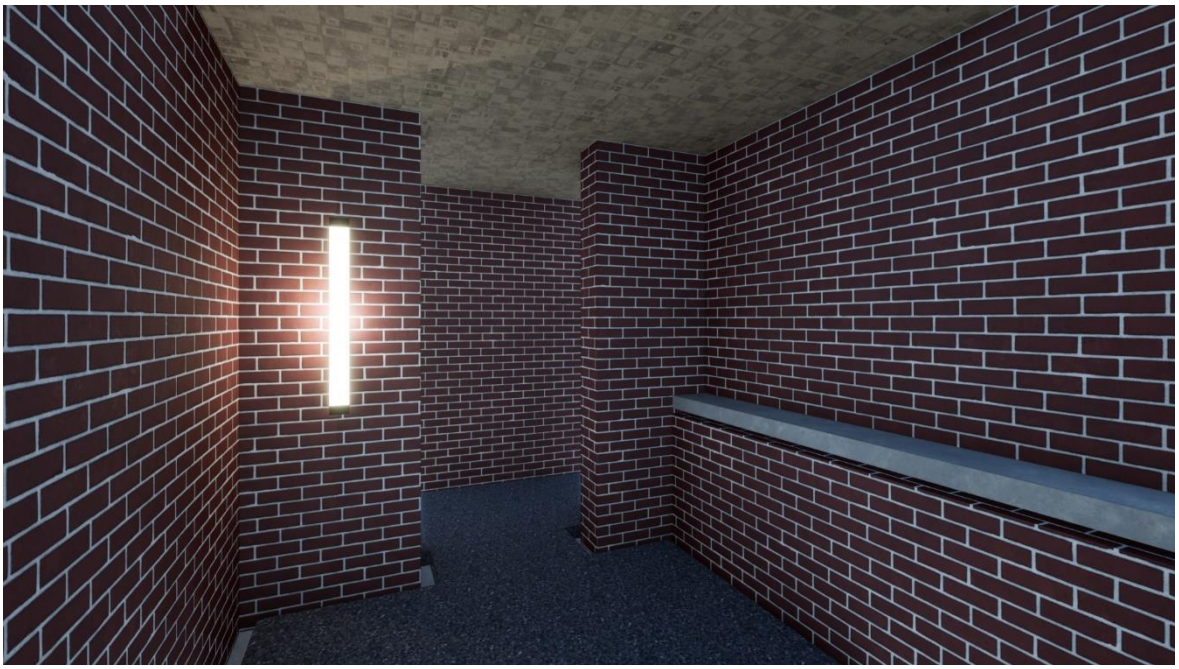


Figure 261
View of neutrino exhibit area

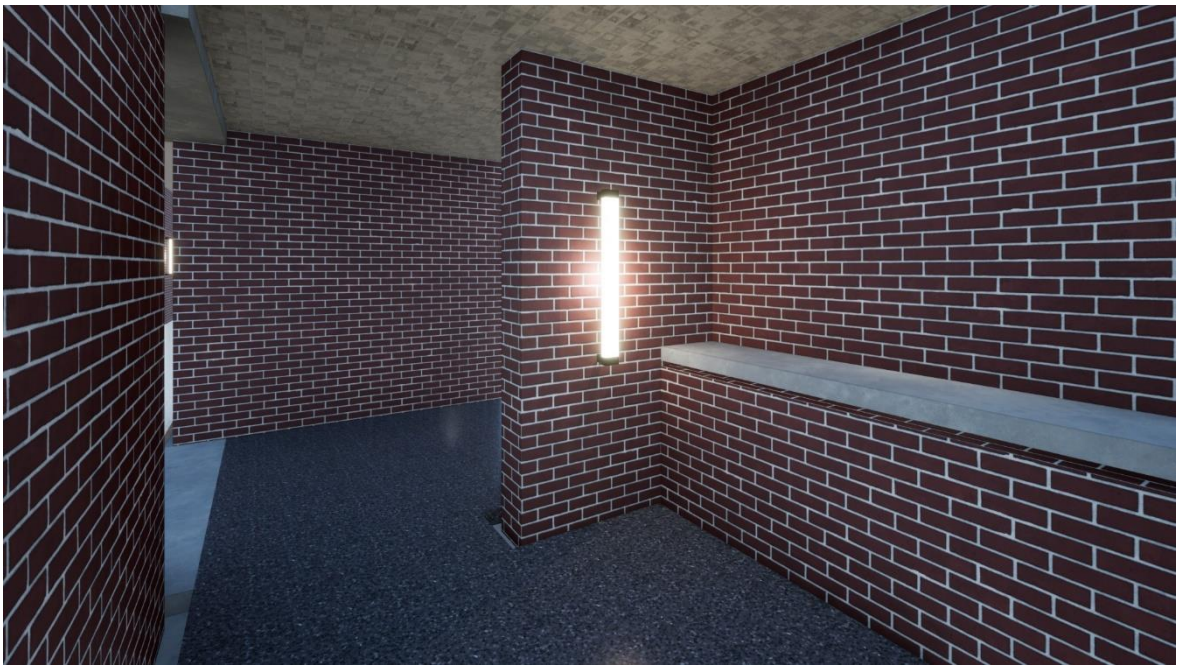
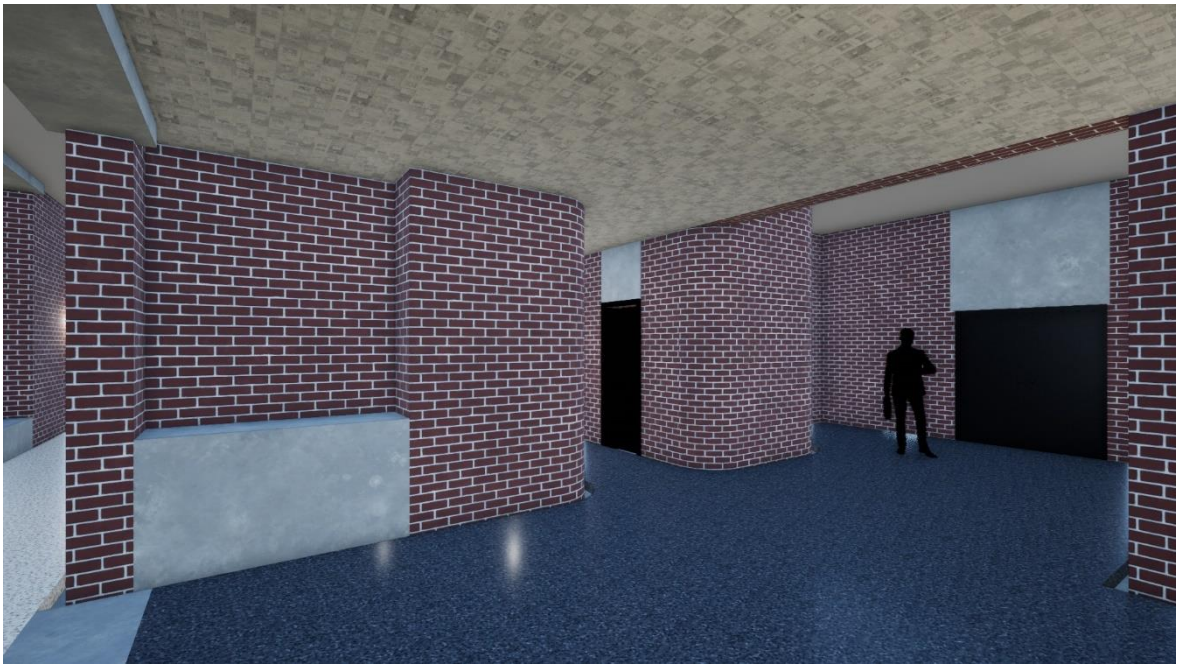


Figure 262
View of elevator waiting area to the south of the dark matter exhibit area



7.8 STRING THEORY

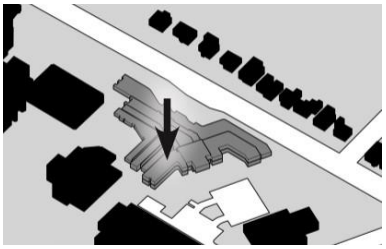


Figure 263
Key plan showing location of string theory exhibit hall

ORGANIZATION & LAYOUT

Like quantum mechanics, string theory implies a hierarchically organized universe whose structure is created from the bottom up by the most fundamental building blocks—in this case, strings. As such, the string theory exhibit hall is organized hierarchically. However, unlike the quantum mechanics exhibit hall, it is not divided into multiple exhibit areas; because string theory posits that there is one fundamental element from which all matter and force is created, I have emphasized a *single* organizing principle in the form of a main pathway that is denoted by floor level, material, and adjacent walls.

This main pathway begins after the exhibit areas that introduce the basic principles of string theory. It extends along most of the length of the exhibit hall. It has proportionally small dimensions compared to the entire room; this is to de-emphasize the path to avoid the impression of a hierarchy imposed upon the space from the top down.

The pathway is not straight and instead changes directions a number of times to both create spaces and reference the vibrating movement of strings. Additionally, I use this nonlinear shape for the main circulatory path to contrast the clarity of quantum mechanics—the Standard Model particularly is extraordinarily well-established by experimental evidence—with the tension between string theory's idealistic aim of explaining the nature of everything with a single element and its *multiplicity* of formulations. The string theory exhibit hall's main circulation, then, follows more directions than the main circulation within the quantum mechanics exhibit hall.

The ceilings in the string theory exhibit hall, like in the quantum mechanics exhibit hall, are a combination of smooth plaster and areas of an accent tile pattern. The accent ceiling tile pattern here is a variation on the ceiling material used in the quantum mechanics exhibit hall. I take the existing tile modules and, as if unwrapping a closed circular dimension, "unwrap" each tile into a new linear tile (see **Figure 267**). These new tiles are then placed adjacent to each other, staggered, to form a new pattern (see **Figure 266**) that references both the unwrapping of higher dimensions and string theory's relationship to the particles of quantum mechanics.

Figure 264
Plan showing the string theory exhibit hall

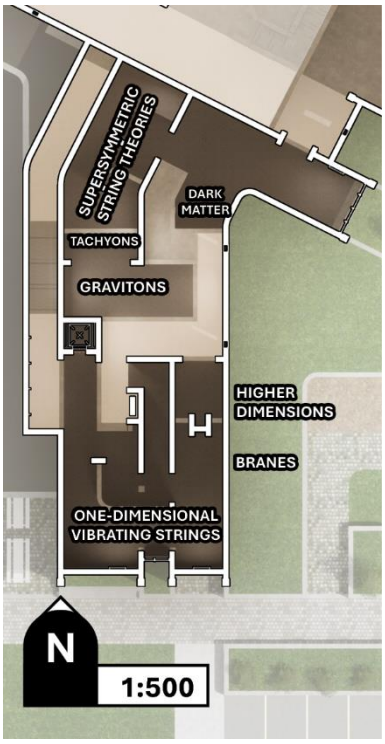
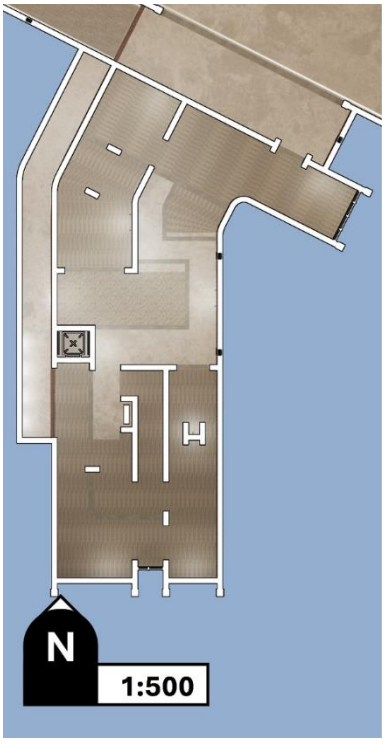


Figure 265
Reflected ceiling plan showing the string theory exhibit hall



The string theory exhibit hall features a particular arrangement of walls that is repeated as an architectural element. To reference the attachment of strings between higher-dimensional surfaces, partial-height brick walls link perpendicular full-height concrete walls.

The light fixtures here are a variation on the light fixtures used in the quantum mechanics exhibit hall. They are also held adjacent to the walls with supports that make the fixtures appear to be floating. However, to express string theory's use of higher dimensions, the shape of the fixtures is broadened so that they appear to be planes rather than lines, or, in other words, so that they have gained a dimension.

Figure 267
String theory ceiling pattern modules

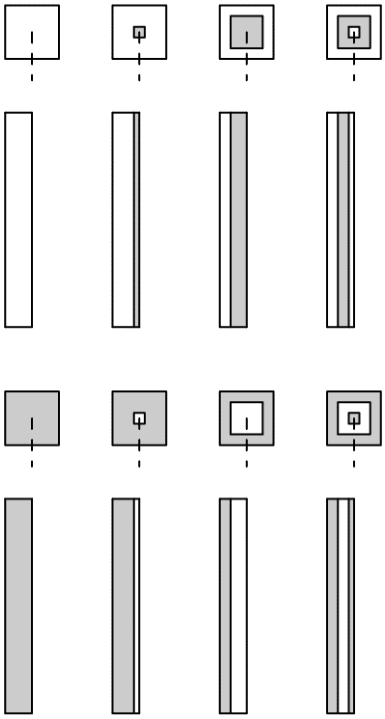
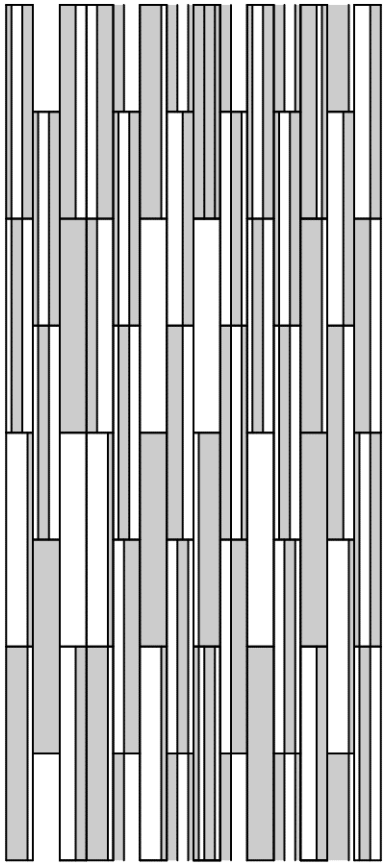


Figure 266
String theory ceiling pattern



ONE-DIMENSIONAL VIBRATING STRINGS

The first exhibit area visitors encounter, to the south of the exhibit hall entrance, explores the one-dimensional vibrating strings of string theory. A single copy of the concrete-brick-concrete arrangement of walls described above divides this space.

BRANES AND HIGHER DIMENSIONS

Following the dividing wall of the previous exhibit area to the east leads visitors to the exhibit area that explores higher-dimensional branes. The northern side of this exhibit area features another copy of the concrete-brick-concrete wall element.

This wall element is visible from the initial floor level as well as an alcove on a raised floor that is accessible by traversing the main pathway. The lower floor level contains the exhibit area about branes, while the upper alcove contains an exhibit area that explores the idea of higher dimensions further; the two concepts and exhibit areas are connected, but they are separated to emphasize the impression that higher dimensions add a secondary layer to the physical world.

Figure 268
Plan showing southern side of string theory exhibit hall

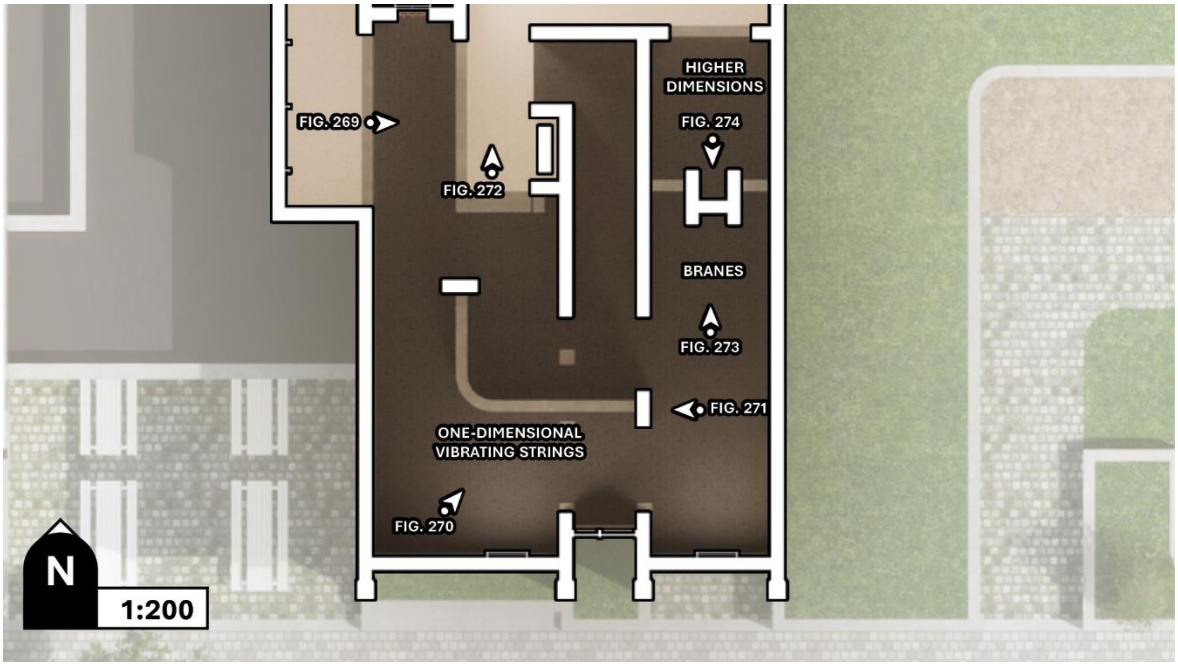


Figure 269
View of entrance to string theory exhibit hall



Figure 270
View of one-dimensional vibrating string exhibit area, from southwest



Figure 271
View of one-dimensional vibrating string exhibit area, from east



Figure 272
View of main pathway in string theory exhibit hall



Figure 273
View of brane exhibit area, from below



Figure 274
View of brane exhibit area, from above



GRAVITONS

Near the centre of the string theory exhibit hall, on the upper floor level, is the exhibit area that explores gravitons. The ceiling here uses the accent tile pattern from the quantum mechanics exhibit hall, as if a missing portion of that exhibit hall has been moved into the string theory exhibit hall; this is a reference to the fact that gravity, and its corresponding force-carrying particle the graviton, are missing from quantum mechanics.

TACHYONS

In an alcove to the northwest of the graviton exhibit area is the tachyon exhibit area. The tachyon, as described in **Section 6.1.2**, is a hypothetical particle able to move faster than the speed of light that is posited by string theory. Supersymmetric versions of string theory no longer require the tachyon, and so the north side of this exhibit area looks out over the supersymmetric string theory exhibit area on the lower level. This is similar to how the higher dimensions exhibit area overlooks the branes exhibit area, but without a connecting feature that is visible from both sides.

Figure 275
Plan showing central portion of string theory exhibit hall



Figure 276
View of graviton exhibit



Figure 277
View of graviton exhibit area



SUPERSYMMETRIC STRING THEORIES

To the northwest of the string theory exhibit hall is the exhibit area that explores supersymmetric string theories. The facet of supersymmetric string theories that I express here is the curling up of higher dimensions to produce the world we experience. To express this architecturally, the concrete-brick-concrete element, with a higher brick portion, is used to create a more enclosed space to elicit the sensation of going *inside* something. A second instance of the concrete-brick-concrete element, with counter-height brick, sits adjacent to the first; this copy is visible from the tachyon exhibit area and serves to both reference the symmetry in supersymmetric string theories and draw attention to the way the higher version of the element encloses the adjoining space. The difference in scale of the walls references the idea that different dimensions can be seen at different scales.

DARK MATTER

To the other side of the end of the main pathway is the dark matter exhibit area. To fit with the theme of dark, as of yet unexplained material, this exhibit area is placed out of the direct paths of light.

Figure 278
View of northern side of string theory exhibit hall

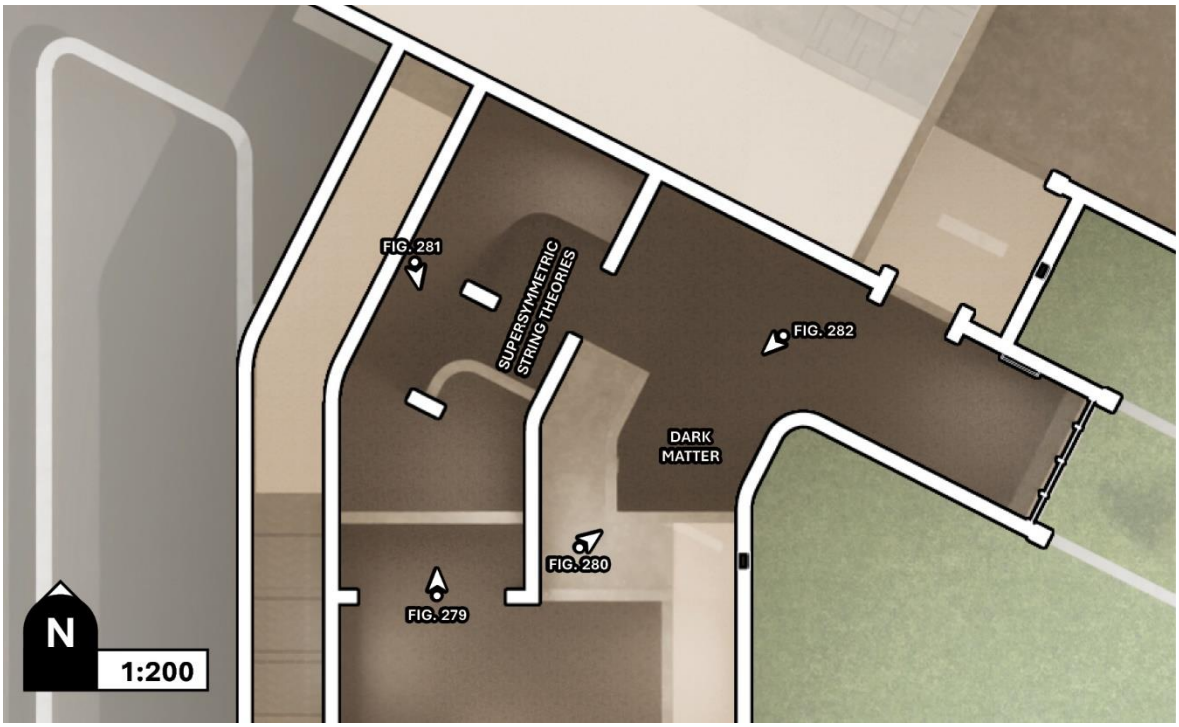


Figure 279
View of tachyon exhibit area

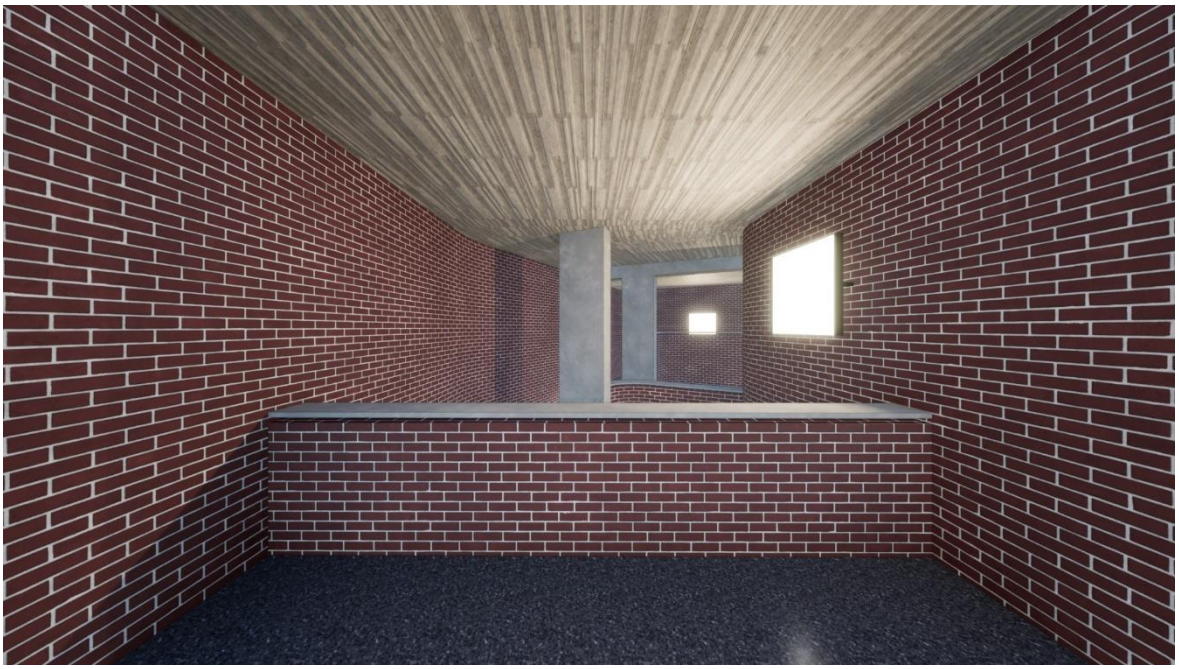


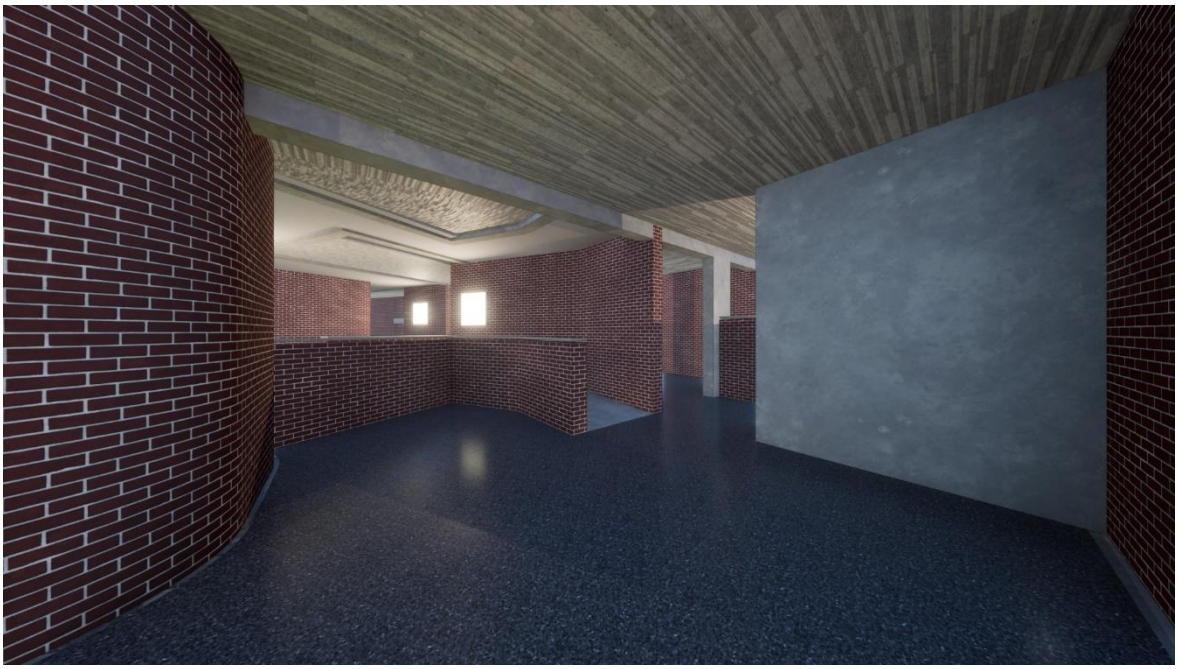
Figure 280
View of ramp and main pathway wrapping around the dark energy exhibit area



Figure 281
View of the supersymmetric string theory exhibit area



Figure 282
View of the dark energy exhibit area



8 CONCLUSION

The goal of physics is to construct a model of the structure of the universe. The contemporary body of knowledge in physics during a given time period, as we have seen, is a factor that contributes to the shaping of the cosmology of that time. Our perception of how the universe is structured affects where we place emphasis in art and architecture, such as why we arrange and order architectural elements the ways that we do.

The way that we think the world is structure is starkly different than it used to be. In dividing each chapter into two sections, one for the scientific context and one analysing the context's implications for architectural characteristics, I noticed that when discussing physics before the Scientific Revolution it was more difficult to separate scientific ideas from the analysis of architectural interpretation. I believe that this is because the more ancient ideas in physics that I examined were not always clearly based in physical observational evidence and data, but instead were more strongly tied to existing cosmological thought. It was not until later, during and after the Scientific Revolution, that the increased use of the scientific method in physics meant that models of the world sought to follow measurable data, rather than fitting observational information into an existing model of the universe.

It seems to me that much of the explicitly cosmological architecture in history has been churches or other religious buildings; this made sense in their cultural contexts because cosmology was highly tied to religion and philosophy. However now, at least within my experience in Canada, cosmology is primarily based in science. This is not to say that scientifically-based cosmological models are less driven by passion—the methods have changed, but the fundamental goal of physics is, like that of religion and philosophy, to construct a framework for understanding the world we live in.

While the scientific method and data now dominate our model of the universe, cosmology's effect on art and architecture remains. Ideas in physics can still be found in art and architecture, whether because of direct influence such as in the case of the Einstein Tower, or because of a more

general shared cultural zeitgeist, such as perhaps is the case between Einstein's theory of relativity and Cubism.[182]

Even when inspired directly by discoveries in physics, artists and architects have a freedom to employ metaphor that is not available to science itself. We can use art to explore the more subjective implications of physics without the requirement for quantitative data. As suggested by the writers of *Einstein and the Changing Worldviews of Physics*, it is possible that "Einstein's personality rather than his scientific theories fascinated artists and writers."[183] It is the *perception* of discoveries in physics—their implications for how we experience the world—that become popular, not necessarily the discoveries in and of themselves. Art, including architecture, allows for the further pursuit of the driving motivations behind physics down an avenue that the tools of theoretical and experimental physics cannot follow. Art and architecture can be used to express physical and emotion experience more tangibly, cutting through layers of math that the average person neither needs nor wants to understand, and arriving at the core of the reasons why we pursue physics at all.

I believe that the application of art towards modern physics that is still largely in progress, such as the search for a theory of quantum gravity, is particularly stimulating. Because any version of a unified theory of physics has not been fully formulated—both loop quantum gravity and string theory have little supporting physical evidence, and entirely different hypotheses abound—it is impossible to know what direction cosmology might take in the future. Expressing the unfinished ideas of physics through art and architecture lets us imagine what the world and its structure could become, and allows non-physicists to engage with the curiosity and joy of discovery that lies at the heart of scientific exploration.

I have indulged my own curiosity about the interpretation of physics with architectural metaphor through the design of a museum of physics and looked at how architecture can be informed by the particular cosmological ideas of modern physics. In the content of the museum, I focused on quantum mechanics and the theory of relativity, in which I have a basic background education, as well as two potential hypothesized solutions to the problem of a unified theory of physics that personally interest me. I also focused on a limited number of its more architectural

[182] Lehner, Renn, and Schemmel, *Einstein and the Changing Worldviews of Physics*, 137.
[183] Lehner, Renn, and Schemmel, 166.

characteristics, such as smoothness versus discontinuity, space versus objects, and hierarchical organization,

However, there are other ways of interpreting the same material. For instance, within the theory of relativity exhibit hall, instead of using the shape of the dividing walls and ramps to evoke the warping of spacetime that we see in the theory of relativity, I could have instead implemented anamorphic projection in some way to imply the stretching and distortion of spacetime, perhaps evoking the morphing of coordinates in a Minkowski spacetime diagram. Likewise, within the quantum mechanics exhibit hall, had I decided to focus not on symmetries and ratios, I could have perhaps used the two-sided disappearing perspective strategy implemented in Julian Voss-Andreae's *Quantum Man* statue to emphasize the duality of matter and waves.

Architectural interpretation of the conceptual material of physics, in any variation, repairs the connection between physics as a "distant" field of study and physics' role as, fundamentally, a way to understand the world we live in. The tangibility of architecture serves as analogy for the ideas in science that lie beyond the barriers of necessary, and yet obfuscating, mathematical analysis. The architecture need not be a literal, direct artistic interpretation of physics, but can remain a metaphorical interpretation of the implications of the theories.

Architectural communication, I believe, relies more on affect, mood, and impressions than on being a science experiment. While accuracy and specificity in science communication is, of course, essential, the metaphorical language and emotional impression that architecture can communicate provide another dimension of information that can better communicate the motivations that drive science.

There are uncountable other ideas and theories in modern physics that also present ample opportunity for architectural exploration, such as the events of the Big Bang or the expansion of the universe. Exploring the models of the world provided by other fields, not only physics, could open up new avenues for architectural expression. There is always more to uncover.

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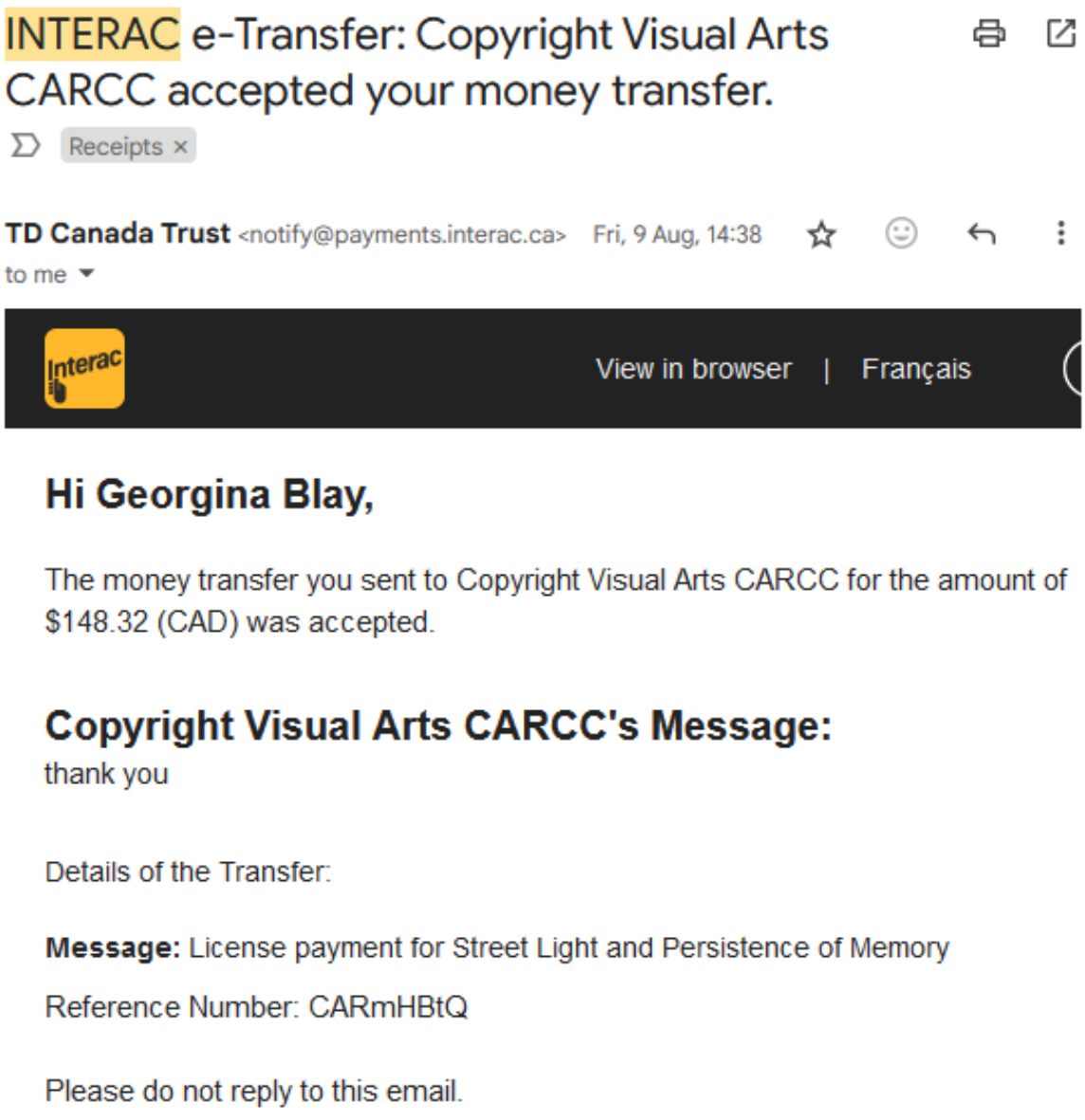
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Aquino, Fran De. “Gravitational Blueshift and Redshift Generated at Laboratory Scale,” n.d.

Architecture and Mathematics from Antiquity to the Future: The 1500s to the Future. Vol. 2. New York, NY: Springer Berlin Heidelberg, 2015.

Barker, Peter, and Bernard R. Goldstein. “Theological Foundations of Kepler’s Astronomy.” *Osiris* 16 (January 2001): 88–113. https://doi.org/10.1086/649340.

Barrau, A., T. Cailleteau, X. Cao, J. Diaz-Polo, and J. Grain. “Probing Loop Quantum Gravity with Evaporating Black Holes.” *Physical Review Letters* 107, no. 25 (December 16, 2011): 251301. https://doi.org/10.1103/PhysRevLett.107.251301.

Bellone, T., F. Fiermonte, and L. Mussio. “The Common Evolution of Geometry and Architecture from a Geodetic Point of View.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-5/W1 (May 16, 2017): 623–30. https://doi.org/10.5194/isprs-archives-XLII-5-W1-623-2017.

Bennett, Jeffrey. *What Is Relativity? An Intuitive Introduction to Einstein’s Ideas and Why They Matter*. New York: Columbia University Press, 2014.

Braham, William W., Jonathan A. Hale, and John Stanislav Sadar, eds. *Rethinking Technology: A Reader in Architectural Theory*. London ; New York: Routledge, Taylor & Francis Group, 2007.

Brüderlin, Markus, Hartmut Böhme, Caspar David Friedrich, and Kunstmuseum Wolfsburg, eds. *The Art of Deceleration: Motion and Rest in Modern Art from Caspar David Friedrich to Ai Weiwei*. Ostfildern: Hatje Cantz, 2011.

Carroll, Sean M. *The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World*. Oxford: Oxford Paperbacks, 2012.

Cohen, Nathan. *Gravity’s Lens: Views of the New Cosmology*. The Wiley Science Editions. New York: Wiley, 1988.

Dine, Michael. *Supersymmetry and String Theory: Beyond the Standard Model*. Cambridge ; New York: Cambridge University Press, 2007.

Dunlap, Richard A. *Particle Physics*. San Rafael CA: Morgan & Claypool Publishers, 2018.

Fix, John D. *Astronomy: Journey to the Cosmic Frontier*. 4th ed. New York, NY: McGraw-Hill Higher Education, 2006.

Fleming, William. “The Element of Motion in Baroque Art and Music,” 2023.

Freeman, Ken, and Geoff McNamara. *In Search of Dark Matter*. Springer-Praxis Books in Popular Astronomy. Berlin ; New York : Chichester, UK: Springer ; Published in association with Praxis Pub, 2006.

Friedman, Susan Stanford. "Scaling Planetarity: *Spacetime* in the New Modernist Studies – Virginia Woolf, H.D., Hilma Af Klint, Alicja Kwade, Kathy Jetñil-Kijiner." *Feminist Modernist Studies* 3, no. 2 (May 3, 2020): 118–47. https://doi.org/10.1080/24692921.2020.1794470.

Gamwell, Lynn, and Neil deGrasse Tyson. *Exploring the Invisible: Art, Science, and the Spiritual*. Revised and Expanded edition. Princeton, New Jersey: Princeton University Press, 2020.

Gato-Rivera, Beatriz. *Antimatter: What It Is and Why It's Important in Physics and Everyday Life*. Cham: Springer International Publishing, 2021. https://doi.org/10.1007/978-3-030-67791-6.

Goldberg, Stanley. *Understanding Relativity*. Boston, MA: Birkhäuser Boston, 1984. https://doi.org/10.1007/978-1-4684-6732-1.

Gonçalves, Clara Germana. "Architecture and Modern Science: The Mathematics of the Circle—Arithmetic and Geometry as Figure and Symbol in the Renaissance and Baroque." In *Modernity, Frontiers and Revolutions*, edited by Maria Do Rosário Monteiro, Mário S. Ming Kong, and Maria João Pereira Neto, 1st ed., 43–49. CRC Press, 2018. https://doi.org/10.1201/9780429399831-6.

Gondhalekar, Prabhakar. *The Grip of Gravity: The Quest to Understand the Laws of Motion and Gravitation*. Cambridge ; New York: Cambridge University Press, 2001.

Gross, Franz, Eberhard Klempt, Stanley J. Brodsky, Andrzej J. Buras, Volker D. Burkert, Gudrun Heinrich, Karl Jakobs, et al. "50 Years of Quantum Chromodynamics: Introduction and Review." *The European Physical Journal C* 83, no. 12 (December 12, 2023): 1125. https://doi.org/10.1140/epjc/s10052-023-11949-2.

Gullberg, Johanna. "Voids and Bodies: August Schmarsow, Bruno Zevi and Space as a Historiographical Theme," n.d.

Hatch, John G. "Some Adaptations of Relativity in the 1920s and the Birth of Abstract Architecture." *Nexus Network Journal* 12, no. 1 (April 2010): 131–47. https://doi.org/10.1007/s00004-010-0024-6.

Henderson, Linda Dalrymple. *The Fourth Dimension and Non-Euclidean Geometry in Modern Art*. Revised edition. Leonardo Book Series. London, England ; Cambridge, Massachusetts: The MIT Press, 2013.

Hersey, George L. *Architecture and Geometry in the Age of the Baroque*. Chicago: University of Chicago Press, 2000.

Isaac Newton Institute. “Grenville Davey,” March 22, 2021. https://www.newton.ac.uk/about/art-artefacts/grenville-davey/.

Julian Voss-Andreae. “Quantum Sculpture: Art Inspired by the Deeper Nature of Reality.” *Leonardo: Journal of the International Society for the Arts, Sciences and Technology* 44, no. 1 (2011): 14-20,44.

Kapferer, Wolfgang. *The Mystery of Dark Matter: In Search of the Invisible*. Astronomers’ Universe. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021. https://doi.org/10.1007/978-3-662-62202-5.

Klint, Hilma af. *Notes and Methods*. New York Chicago: University of Chicago Press, 2018.

Kowalczyk, Stefan, Quinten Krijger, Maarten van de Meent, Jorn Mossel, Gerben Schooneveldt, and Bart Verouden. “Constraints on Large Extra Dimensions,” 2003.

Koyré, Alexandre. *From the Closed World to the Infinite Universe*. Publications of the Institute of the History of Medicine, the Johns Hopkins University, Third series, the Hideyo Noguchi lectures, v. 7. Baltimore London: Johns Hopkins University Press, 1957.

Kumar, Manjit. *Quantum: Einstein, Bohr and the Great Debate about the Nature of Reality*. 1. American ed. New York, NY: Norton, 2010.

Kurzyk, Dariusz. “Introduction to Quantum Entanglement.” *Theoretical and Applied Informatics* 24, no. 2 (January 1, 2012). https://doi.org/10.2478/v10179-012-0010-7.

Lehner, Christoph, Jürgen Renn, and Matthias Schemmel, eds. *Einstein and the Changing Worldviews of Physics*. Boston: Birkhäuser Boston, 2012. https://doi.org/10.1007/978-0-8176-4940-1.

Li, Dongjun, Pratik Wagle, Yanbei Chen, and Nicolás Yunes. “Perturbations of Spinning Black Holes beyond General Relativity: Modified Teukolsky Equation.” *Physical Review X* 13, no. 2 (May 25, 2023): 021029. https://doi.org/10.1103/PhysRevX.13.021029.

LIGO Lab | Caltech. “FAQ.” Accessed May 14, 2024. https://www.ligo.caltech.edu/page/faq.

LIGO Lab | Caltech. “LIGO Celebrates First Anniversary of Historic Gravitational Wave Detection!” Accessed May 14, 2024. https://www.ligo.caltech.edu/news/ligo20160914.

LIGO Lab | Caltech. “What Are Gravitational Waves?” Accessed June 28, 2024. https://www.ligo.caltech.edu/page/what-are-gw.

Mackay, Alan L. “Lucretius: Atoms and Opinions.” *Interdisciplinary Science Reviews* 16, no. 2 (1991).

Mateo, José Luis, and Florian Sauter, eds. *Earth - Water - Air - Fire: The Four Elements and Architecture*. New York, N.Y.: ACTAR, 2014.

Mendelsohn, Erich, Regina Stephan, and Charlotte Benton, eds. *Eric Mendelsohn: Architecture, 1887-1953*. New York: Monacelli Press, 1999.

Millard, Charles W. “Modernist Architectural Space.” *The Hudson Review* 20, no. 3 (1967): 448. https://doi.org/10.2307/3849762.

Miller, David Marshall. *Representing Space in the Scientific Revolution*. 1st ed. Cambridge University Press, 2014. https://doi.org/10.1017/CBO9781107110656.

Myburgh, Brittany. “Space-Time and Utopia: Notes on Artistic Engagement with Physics from Cubism to Laszlo Moholy-Nagy,” 2022.

Natario, Jose. *General Relativity Without Calculus: A Concise Introduction to the Geometry of Relativity*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011. https://doi.org/10.1007/978-3-642-21452-3.

Panchbhai, Arati S. “Wilhelm Conrad Röntgen and the Discovery of X-Rays: Revisited after Centennial.” *Journal of Indian Academy of Oral Medicine and Radiology* 27, no. 1 (2015): 90. https://doi.org/10.4103/0972-1363.167119.

Passinmäki, Pekka. “Can the New Cosmology, Cosmogenesis, Serve as a Basis for a Shared Value System in Architecture? On Charles Jencks.” *Architectural Research Quarterly* 17, no. 1 (March 2013): 19–23. https://doi.org/10.1017/S1359135513000316.

Pati, Jogesh C., and Abdus Salam. “Lepton Number as the Fourth ‘Color.’” *Physical Review D* 10, no. 1 (July 1, 1974): 275–89. https://doi.org/10.1103/PhysRevD.10.275.

Paul G. Hewitt. “Focus on Physics: Newton’s Prisms.” *The Science Teacher* 88, no. 2 (December 2020): 16–17.

Pérez-Gómez, Alberto. *Architecture and the Crisis of Modern Science*. Cambridge, Massachusetts: MIT Press, 1983.

Plus Maths. “String Theory, Duality and Art: How the Higgs Boson and Turner Prize Collide.” Accessed May 11, 2024. https://plus.maths.org/content/string-theory-duality-and-art-how-higgs-boson-and-turner-prize-collide.

Robbin, Tony. *Shadows of Reality: The Fourth Dimension in Relativity, Cubism, and Modern Thought*. New Haven: Yale University Press, 2006.

Rouaud, Mathieu. “Einstein’s Elevator: World Lines, Michelson–Morley Experiment and Relativistic Paradox.” *Physics* 4, no. 3 (August 11, 2022): 892–911. https://doi.org/10.3390/physics4030058.

Rovelli, Carlo. *Reality Is Not What It Seems: The Journey to Quantum Gravity*. Translated by Simon Carnell and Erica Segre. First Riverhead trade paperback edition. New York: Riverhead Books, 2018.

Schmitz, Wouter. *Understanding Relativity: A Conceptual Journey Into Spacetime, Black Holes and Gravitational Waves*.

The Frontiers Collection. Cham: Springer International Publishing, 2022. https://doi.org/10.1007/978-3-031-17219-9.

Skinner, Stephen. *Sacred Geometry: Deciphering the Code*. 1st pbk. ed. New York: Sterling, 2009.

Small. “Circling Round Vitruvius, Linear Perspective, and the Design of Roman Wall Painting.” *Arts* 8, no. 3 (September 14, 2019): 118. https://doi.org/10.3390/arts8030118.

Smolin, Lee. *The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next*. Boston: Houghton Mifflin, 2006.

———. *Three Roads to Quantum Gravity*. Science Masters. New York, N.Y: Basic Books, 2002.

Smoothey, Marion. *Ratio and Proportion*. New York: Marshall Cavendish, 1995.

Sten Odenwald. *Quantum Physics: The Complete Guide to Quantum Physics, Including Wave Functions, Heisenberg’s Uncertainty Principle and Quantum Gravity*. Knowledge in a Nutshell. Arcturus Digital Limited, 2019.

The Museum of Modern Art. “John Latham: Time Base and the Universe | MoMA.” Accessed May 17, 2024. https://www.moma.org/calendar/exhibitions/4867.

Tipler, Paul Allen, and Ralph A. Llewellyn. *Modern Physics*. 6th ed. New York: W. H. Freeman and Co, 2012.

Trudeau, Richard J. *The Non-Euclidean Revolution*. Boston, MA: Birkhäuser Boston, 1986. https://doi.org/10.1007/978-0-8176-4783-4.

Wittkower, Rudolf. *Architectural Principles in the Age of Humanism*. London New York: Academy Editions St. Martin’s Press, 1988.

APPENDIX A

This appendix includes a selection of design process sketches.

Figure 283
Sketch page from July 21st, 2023 showing the process of designing the main gestures of the building.

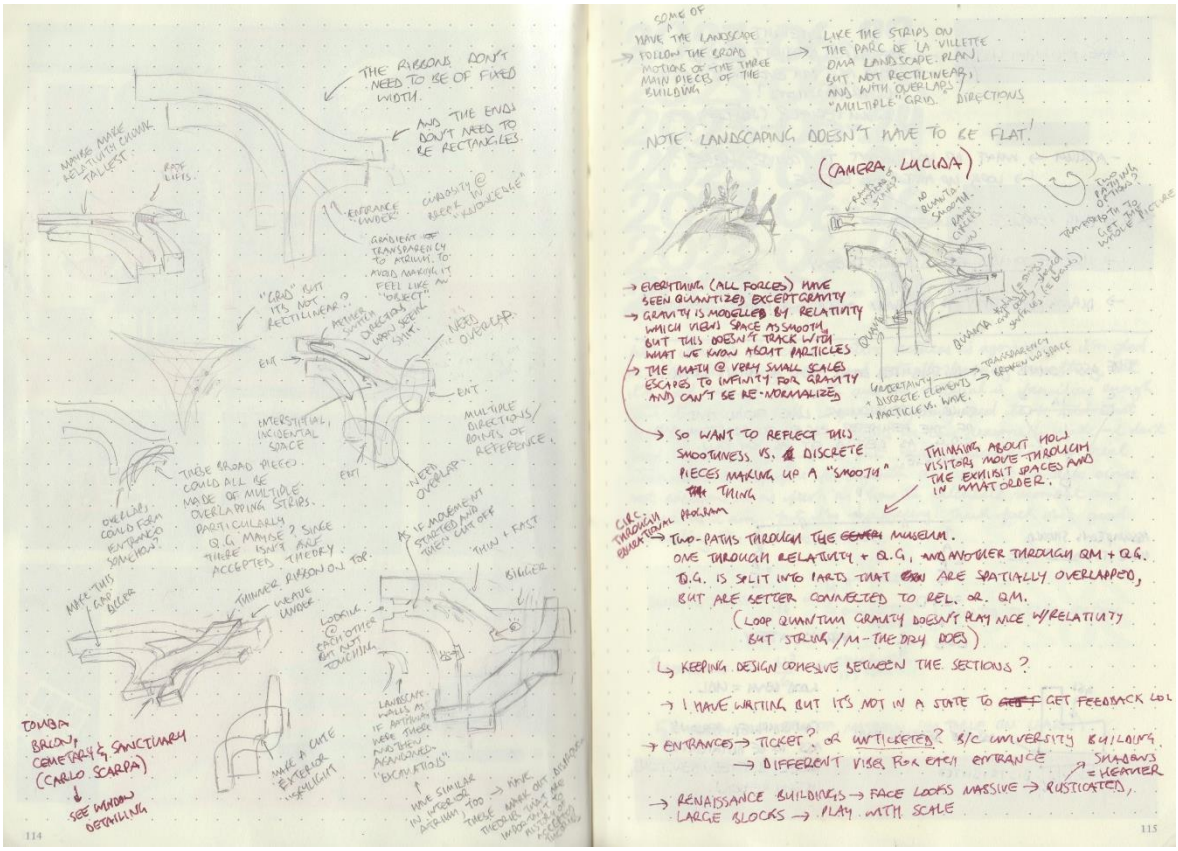


Figure 284
Sketch page from November 27th and 28th, 2023. The left pages shows process sketches regarding the general relativity exhibit hall. The right page shows process work regarding the exterior façades.

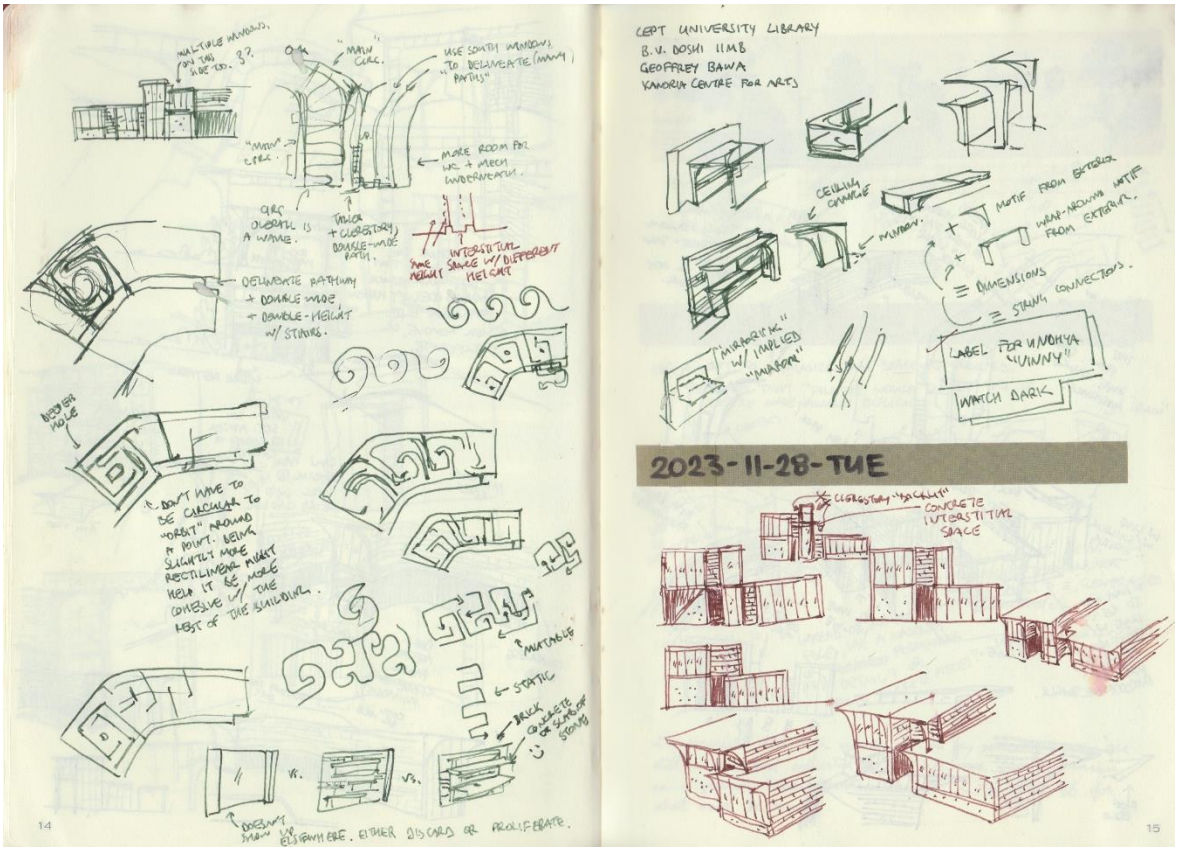


Figure 285
Sketch page from March 12th, 2024 showing process work for the layout of the string theory exhibit hall.

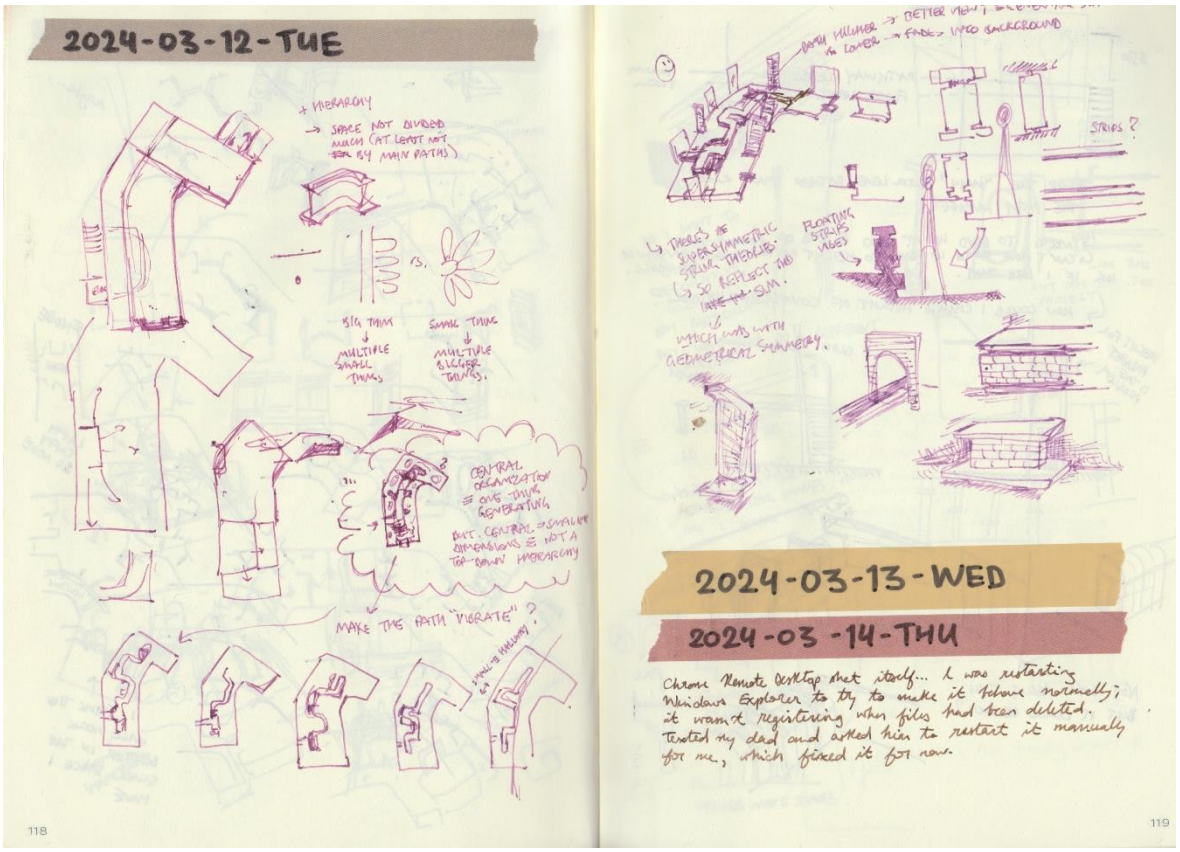


Figure 286
Sketch page from May 6th and 7th, 2024 showing process work for the accent brick patterns in the central space.

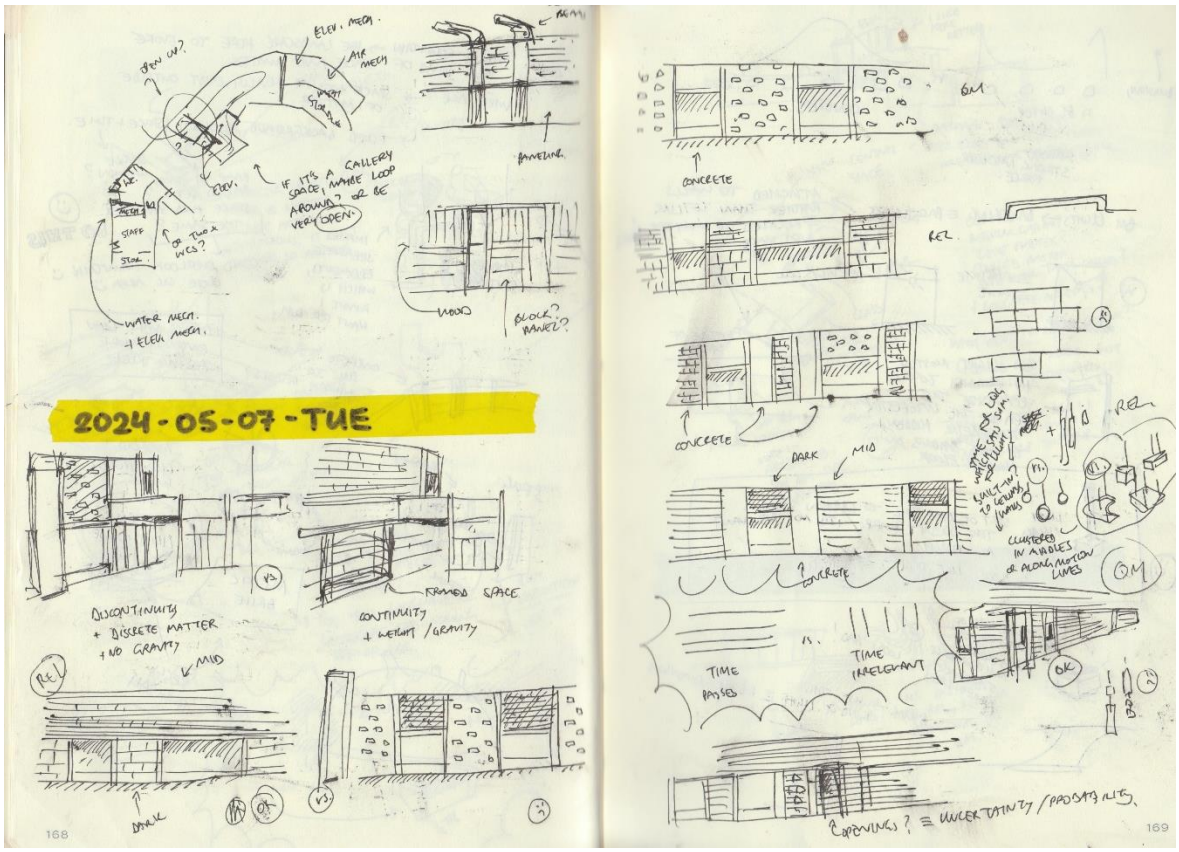


Figure 287
Sketch page from May 8th, 2024 showing process sketches for the west garden and fountain.

