Greene, Brian. The Elegant Universe: Superstrings, Hidden Dimensions and the Quest for the Ultimate Theory. New York: Vintage Books, 2000, 448pp.

Outline Prepared by Rev. William S. Wick, Norwich University Chaplain (12/18/2013)

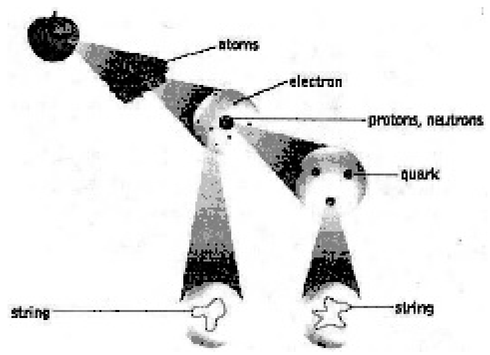
I. Preface p.ix
   - A. During the last thirty years of his life, Albert Einstein sought [but never realized] a so-called unified field theory capable of describing nature's forces within a single, all-encompassing, coherent framework.
   - B. ... physicists believe they have found a framework for stitching these insights together into a seamless whole - capable of describing all phenomena: *superstring theory*. p.x
   - C. Elegant Universe is an attempt to make these insights accessible to a broad spectrum of readers.
   - D. Superstring theory draws on many of the central discoveries in physics (and Greene focuses on the evolving understanding of space and time).
   - E. ... cutting-edge research has integrated [Einstein's] discoveries into a quantum universe with numerous hidden dimensions coiled into the fabric of the cosmos - dimensions whose geometry may well hold the key to some of the most profound questions ever posed. p.xi
   - F. Greene's has focuses on the impact superstring theory has on concepts of space and time.

II. Part I: The Edge of Knowledge (Chapter One: Tied Up with String) p.1
   - A. Introduction p.3
     - 1. two foundational pillars upon which modern physics rests:
       - a. Albert Einstein's *General Relativity* (a theoretical framework for understanding the universe on the largest of scales (the immense expanse of the universe itself)
       - b. *quantum mechanics* (a theoretical framework for understanding the universe on the smallest of scales - (atomic/subatomic particles)
     - 2. As ... currently formulated, general relativity and quantum mechanics are mutually incompatible and *cannot both be right*.
     - 3. Superstring theory ... describing matter at its most fundamental level [potentially] resolves the tension between general relativity and quantum mechanics. p.4
       - a. in this framework general relativity and quantum mechanics *require one another* for the theory to make sense.
       - b. this theory has the potential to show that all of the happenings in the universe are reflections of one grand physical principle/one master equation. p.5
       - c. the conflict between general relativity and quantum mechanics is the third in a sequence of pivotal conflicts ... each of whose resolution has resulted in ... revisions of our understanding of the universe.
   - B. The Three Conflicts
     - 1. Conflict #1: (1800's) Puzzling Properties of the Motion of Light
       - a. according to Isaac Newton one can catch up with a departing beam of light
       - b. according to James Clerk Maxwell's laws of electromagnetism one cannot catch up with a departing beam of light
       - c. Einstein's *theory of special relativity* resolved this conflict (overturning the understanding of space and time)
         - (1) space and time cannot be thought of as universal concepts experienced identically by everyone
         - (2) space and time are malleable constructs whose form and appearance depends on one's state of motion
     - 2. Conflict #2:
       - a. Einstein's work [showed] that no object, influence or disturbance can travel faster than the speed of light.
       - b. But Newton's universal theory of gravitation involves influences that are

        transmitted over vast distances of space instantaneously. p.6

        - c. Einstein resolved the conflict by offering a new conception of gravity in his 1915 *general theory of relativity*.
            - (1) space and time are influenced by one’s state of motion and can warp and curve in response to the presence of matter or energy
            - (2) distortions to the fabric of space and time transmit the force of gravity from one place to another
            - (3) space and time [are not] an inert backdrop [for] the events of universe ... rather, through *special and* then *general relativity*, they are intimate players in the events themselves
    - 3. Conflict #3: The Incompatibility b/tw Quantum Mechanics and General Relativity
        - a. the discovery of *general relativity* resolved one conflict butt led to another.
        - b. Beginning in 1900 physicists developed *quantum mechanics* in response to a number of glaring problems that arose when 19th century conceptions of physics were applied to the microscopic world.
        - c. The gently curving geometrical form of space emerging from general relativity is at loggerheads with the frantic, roiling, microscopic behavior of the universe implied by quantum mechanics.
            - (1) mid-1980's: *string theory* offered a resolution to the central problem of modern physics
            - (2) building on special and general relativity, string theory requires its own severe revamping of [the] conceptions of space and time
            - (3) according to string theory [the] universe has many more dimensions than [the three] that meet the eye - dimensions that are tightly curled into the folded fabric of the cosmos
- C. The Universe at Its Smallest: What We Know about Matter p.7
    - 1. Far from being the most elementary material constituent, atoms consist of a *nucleus*, containing *protons* and *neutrons*, [and are] surrounded by a swarm of orbiting *electrons*.
    - 2. In 1968 experimenters at the Stanford Linear Accelerator Center ... found that *protons* and *neutrons* are not fundamental, either.
        - a. each consists of three smaller particles called *quarks*
        - b. *quarks* ... come in two varieties: *up* and *down*
        - c. a proton consists of two *up quarks* and one *down quark*
        - d. neutrons consist of two *down quarks* and one *up quark*
    - 3. Everything seen in the terrestrial and celestial world appears to be made from combinations of *electrons*, *up-quarks* and *down-quarks*.
        - a. no experimental evidence indicates that any of these three particles is built up from something smaller ... but a great deal of evidence indicates that the universe itself has additional particulate ingredients p.8
            - (1) mid-1950's Frederick Reines and Clyde Cowan found conclusive experiential evidence for a fourth kind of fundamental particle called a *neutrino* (now called a *electron-neutrino*)(such a particle was predicted in the early 1930s by Wolfgang Pauli*)*
            - (2) late 1930s another particle called a *muon* was discovered by physicists studying cosmic rays
            - (3) physicists have found ...
                - (a) four more quarks: *charm*, *strange*, *bottom*, *top*
                - (b) the *tau* (a heavier cousin of the electron)
                - (c) two particles similar to the *electron-neutrino*: *muon-neutrino*, *tau-*

        - *neutrino*
    - (4) each of these particles has an *antiparticle* partner - a particle of identical mass but opposite in certain other respects
      EXAMPLE: a *positron* is the antiparticle of an *electron* with exactly the same mass as an *electron* but its electric charge is +1 whereas the electric charge of the *electron* is -1
    - (5) when in contact, matter and antimatter can annihilate one another to produce pure energy p.9
  - b. these particles fall into three groups often called *families*
    - (1) family one: *electrons, electron-neutrinos*, *up-quark*s, *down-quark*s
    - (2) family two: *muon*s, *muon-neutrino*s, *charm quark*s, *strange quark*s
    - (3) family three: *tau*s, *tell-neutrino*s, *top quark*s, *bottom quark*s
- D. The Forces, or, Where's the Proton? p.10
  - 1. interactions between various objects and materials can be reduced to combinations of **four fundamental forces**.
    - a. the *gravitational force* (the mass of an object measures how much gravitational force it can exert as well as feel)
    - b. the *electromagnetic force* (the force driving all of the conveniences of modern life - all forms of electronics)
      NOTE: microscopically, the electric charge of the particle plays the same role for the electromagnetic force as mass does for gravity: it determines how strongly the particle can exert as well as respond electromagnetically
    - c. two *nuclear forces* (whose strength rapidly diminishes over all but sub-atomic distance scales)
      - (1) the *strong force*
        - (a) keeps *quarks* glued together inside of *protons* and *neutrons*
        - (b) keeps *protons* and *neutrons* tightly crammed together inside atomic nuclei
      - (2) the *weak force* (responsible for the radioactive decay of substances such as uranium and cobalt) p.11
  - 2. two features common to all four fundamental forces:
    - a. 1st, at a microscopic level all the forces have an associated particle that can be considered the smallest packet or bundle of the force
      - (1) *photons* are the smallest bundles of the *electromagnetic force*
      - (2) *weak gauge bosons* are the smallest constituents of the *weak force*
      - (3) *gluons* are the smallest constituents of the *strong force*
      - (4) **gravitons* are the smallest constituents of the *gravitational force*
        *NOTE: physicists believe in their existence but such has yet to be experimentally confirmed
    - b. 2nd, particles are endowed with certain amounts of "strong charge" and "weak charge" that determine how they are affected by the strong and weak forces
  - 3. The universe would be a vastly different place if the properties of the matter and force particles were even moderately changed. p.12
  - 4. there a scientific explanation for *why* they have these properties: string theory p. 13
- E. String Theory: The Basic Idea
  - 1. Particles are the "letters" of all matter (electrons, electron-neutrino's, up quarks, down quarks, muons, muon-neutrinos, charm quarks, strange quarks, taus, tau-neutrinos, top quarks, bottom quarks).



- 2. If these particles could be examined with greater precision one would find that each is not point like, but instead consists of a tiny one-dimensional *loop*. p.14
  - a. Like an infinitely thin rubber band, each particle contains a vibrating, oscillating, dancing filament named a *string.*
  - b. *String theory* adds the new microscopic layer of a vibrating loop to the previously known progression from atoms through protons, neutrons, electrons and quarks.
  - c. ... replacement of point-particle material constituents with strings resolves the incompatibility between quantum mechanics and general relativity.

F. String Theory as the Unified Theory of Everything (T.O.E.) p.15

- 1. Einstein ... [searched for] the so-called *unified field theory* that he hoped would show that the forces of gravity and electromagnetism were really manifestations of one grand underlying principle.
- 2. [This] dream has become the Holy Grail of modern physics and a sizable part of the physics and mathematics community is convinced that *string theory* provides the answer.
- 3. From one principle (that everything at its most microscopic level consists of combinations of vibrating strands) string theory provides a single explanatory framework capable of encompassing all forces and all matter.
- 4. *String Theory* proclaims that the observed particle properties are a reflection of the various ways in which a string can vibrate.
  - a. Just as the strings on a violin have resonant frequencies at which they prefer to vibrate the same holds true for the loops of string theory.
  - b. each of the patterns of vibration of a string appears as a particle whose mass and force charges are determined by the string's oscillatory pattern.
    - (1) the electron is a string vibrating one way, the up-quark is a string vibrating another way, and so on.
    - (2) particle properties are the manifestation of one and the same physical feature: resident patterns of vibration of fundamental loops of string.p.16
    - (3) force particles are also associated with particular patterns of string vibration - hence, all matter and all forces [are] unified under the same rubric of microscopic string oscillations
- 5. *String Theory* is possibly the "theory of everything" (T.O.E.)/the "ultimate" or "final" theory underlying all others [and] not requiring or allowing a deeper explanatory base.
  - a. many string theorists think of a T.O.E. in the more limited sense of a theory that can explain the properties of the fundamental particles and properties of the forces by which they interact and influence one another.
  - b. others argue that developments such as *chaos theory* [show] that new kinds of laws come into play when the level of complexity of a system increases. p.17
- 6. discovery of the T.O.E. would provide the firmest foundation on which to build [an] understanding of the world. (its discovery would mark a beginning, not an end).

G. The State of String Theory p.18

- 1. *String Theory* is such a deep and sophisticated theoretical structure that [there is] far to go before full mastery can be achieved (i.e. *string theory* is a work in progress).
- 2. If *String Theory* is right, the microscopic fabric of [the] universe is a richly intertwined multidimensional labyrinth within which the strings of the universe endlessly twist and

vibrate, rhythmically beating out the laws of the cosmos. Far from being accidental details, the properties of nature's basic building blocks are deeply entwined with the fabric of space and time.

   3. the mathematics of string theory is so complicated that, to date, no one even knows the exact equations of the theory (physicists know only approximations to these equations, and even the approximate equations are so complicated that they as yet have been only partially solved) p.19
   4. *String Theory* is part of a grander synthesis: M-theory p.20
   5. research by hundreds of dedicated physicists and mathematicians from numerous countries have given [a] well-founded hope [of string theory being] on the right and possibly final track

III. Part Two: The Dilemma of Space, Time, and the Quanta p.21

- A. Chapter Two: Space, Time, and the Eye of the Beholder p.23
  - 1. Introduction
    - a. mid-1800s Scottish physicist James Clerk Maxwell succeeded in uniting electricity and magnetism in the framework of the *electromagnetic field*.
      - (1) electromagnetic disturbances travel at a fixed and never-changing speed equal to that of light. p.24
      - (2) visible light itself is a particular kind of electromagnetic wave
      - (3) all electromagnetic waves (visible light among them) never stop, never slow down (light *always* travels at light speed).
    - b. [Einstein wondered [in keeping with Newton's laws of motion] if one chases after a beam of light at light speed would the light waves appear to be stationary/would light stand still?
    - c. According to Maxwell's theory there is simply no such thing as stationary light.
    - d. Einstein resolved the conflict through his *special theory of relativity* - i.e. the essential concern of special relativity is to understand precisely how the world appears to individuals, often called "observers," who are moving relative to one another.
  - 2. Intuition and Its Flaws p.25
    - a. opening illustration
      - (1) trees alongside a highway appear to be moving from the viewpoint of a driver but appear stationary to a hitchhiker sitting on a guardrail
      - (2) the dashboard of an automobile does not appear to be moving from the viewpoint of a driver but, like the rest of the car, appears to be moving from the viewpoint of a stationary hitchhiker
      - (3) special relativity proclaims that the differences in observations between two such individuals are more subtle and profound
    - b. S*pecial Relativity* claims that observers in relative motion will have different perceptions of distance and of time.
      - (1) identical wristwatches worn by two individuals in relative motion will tick at *different rates* and will not agree on the amount of time that elapses between chosen events
      - (2) observers in relative motion carrying identical tape measures will not agree on the lengths of distances measured
      - (3) space and time, as measured by distances and durations, are not experienced identically by everyone
    - c. *Special Relativity* resolves the conflict between intuition about motion and the properties of light (but individuals moving with respect to each other will not

agree on their observations of either space or time)
   - d. The effects of special relativity depend upon how fast one moves.

3. The Principle of Relativity p.28
   - a. Two deeply rooted structures form the foundation of special relativity:
     - (1) the properties of light
     - (2) *the principle of relativity* - i.e. whenever discussing speed or velocity (an object's speed and its direction of motion) one must specify precisely who or what is doing the measuring
       - (a) in space one might consider oneself to be stationary and not moving while someone else passes by
       - (b) in space the other individual might consider himself/herself to be stationary while the other person passes by
       - (c) or unknown to each could be moving and pass by each other
   - b. The concept of motion is relative - one can speak about the motion of an object but only relative to or by comparison with another (i.e. there is no "absolute" notion of motion - motion is relative) p.29
   - c. *Force-free* motion has meaning only by comparison with other objects.
     - (1) if forces are involved, they cause changes in the velocity of the observers (changes in speed and/or in direction)and these changes can be felt
     - (2) constant velocity/force-free motion is relative - not so non-constant velocity or accelerated motion p.30

4. The Speed of Light p.31
   - a. Light travels at 670,000,000 mph (186,000 mps) regardless of benchmarks for comparison)
   - b. If one was speeding away from a light source, based on the traditional Newtonian worldview, one would expect to measure a slower speed for the oncoming photons. p.32
   - c. Careful analysis and interpretation of Maxwell's electromagnetic theory of light demonstrates this is not what would happen.
   - d. *Even though [one is] retreating, [one] will still measure the speed of the approaching photons as 670,000,000 mph*
     - (1) the speed of approaching photons is always 670,000,000 mph
     - (2) the same is also true if [one] run[s] toward oncoming photons or chase[s] after them - their speed of approach or recession is completely unchanged
   - e. *Regardless of relative motion between the source of photons and the observer, the speed of light is always the same.*
     - (1) ... the speed of light received from a moving star is the *same* as that from a stationary star - 670,000,000 mph. p.33
     - (2) no matter how hard [one] chase[s] after a light beam, it still retreats from [the observer] at light speed.
   - f. Einstein realized that the constancy of light's speed spelled the downfall of Newtonian physics.

5. Truth and Consequences
   - a. speed is a measure of how far an object can travel in a given duration of time.
   - b. distance is a notion about space - a measure of how much space is b/tw two points
   - c. duration is a notion about time - how much time elapses b/tw two events
   - d. thus, speed is connected with notions of space and time.

6. The Effect on Time: Part I p.34
   - a. the constancy of the speed of light show[s] that the familiar everyday conception

of time is wrong - things that are simultaneous from the viewpoint of some observers will not be simultaneous from the viewpoint of others, if the two groups are in relative motion. p.36

b. light does not speed up or slow down - its constancy requires that the notion must be given up that simultaneity is a universal concept [upon which] everyone, regardless of their state of motion, agrees (i.e. observers in relative motion will not agree on which events occur at the same time).

7. The Effect on Time: Part II p.37

a. It is difficult to give an abstract definition of time ...

b. ... [one] can [pragmatically] define time to be that which is measured by clocks ... (devices that undergo “perfectly regular cycles of motion” - the meaning of “perfectly regular cycles of motion” implicitly involves a notion of time, since “regular” refers to equal time durations elapsing for each cycle).

c. goal: to understand how motion affects the passage of time

d. [Greene] first considers only motion at a constant velocity (i.e. how motion affects the passage of time and how it fundamentally affects the ticking of *any* and *all* clocks regardless of their particular design or construction). p.38

e. [Consider a] “light clock”: two small mirrors mounted on a bracket facing one another, with a single photon of light bouncing back and forth between them

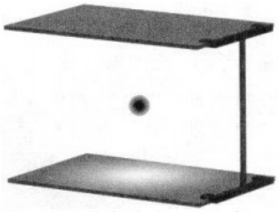


Figure 2.1 A light clock consists of two parallel mirrors with a photon that bounces between them. The clock "ticks" each time the photon completes a round-trip journey.

(1) a “tick” on a light clock occurs every time the photon completes a round-trip

(2) using the light clock as a stopwatch to measure the time elapsed between events, count how many “ticks” occur during the period of interest and multiply by the time corresponding to one tick

(3) imagine that one is watching the passage of time by looking at a ticking light clock placed on a stationary table p.39

(4) a second light clock slides by on the table, moving at constant velocity

(5) will the moving light clock tick at the same rate as the stationary light clock?

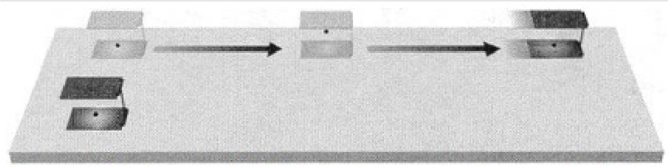
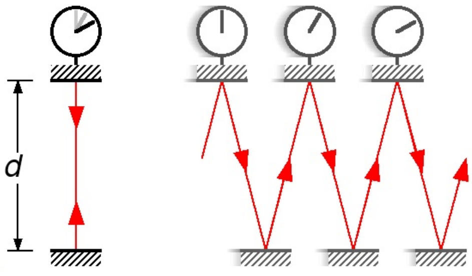


Figure 2.2 A stationary light clock in the foreground while a second light clock slides by at constant speed.



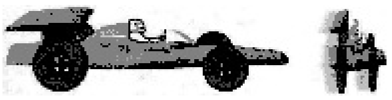
(6) consider the path, from [the observer’s] perspective, that the photon in the sliding clock must take in order for it to result in a tick

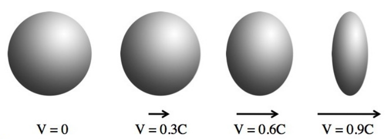
    - (7) from the observer’s perspective, the photon moves at an angle/a diagonal path which seems *longer* than a straight up-and-down path
    - (8) the sliding clock’s photon travels at the same speed as the stationary clock’s photon but since it must travel farther to achieve one tick it will tick *less frequently* (from the observer’s perspective the moving light clock ticks more slowly than the stationary light clock) p.40
    - (9) since the number of ticks directly reflects how much time has passed the passage of time has slowed down for the moving clock
    - (10) the time difference b/tw stationary and moving clocks depends on how much farther the sliding clock’s photon must travel to complete each round-trip journey wh/in turn depends on how quickly the sliding clock is moving from the viewpoint of the stationary observer
    - (11) the rate of the ticking of the sliding clock becomes slower and slower as it moves faster and faster p.41

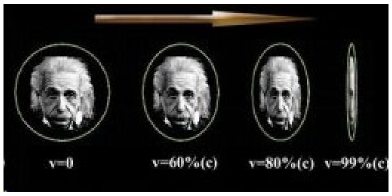
8. Life on the Run
    - a. Time elapses more slowly for an individual in motion than it does for **a** stationary individual.
    - b. ... would one live longer by being in motion rather than staying stationary?
    - c. ... if time elapses more slowly for an individual in motion than for an individual at rest, then this disparity should apply not just to time as measured but also to time as measured by heartbeats ...
    - d. Yes, but living longer is due to *time elapsing more slowly* [and] although [appearing] to live longer than [if] stationary, its rate as well as everything else in its life slows down as well. p.42
    - e. it’s as if [one lives] in slow motion [and] live[s] longer than [one who is] stationary but the “amount of life” is precisely the same.
    - f. for the fast-moving people (from their perspective) it’s life as usual. From [observers at a stationary perspective] they are living life in hyper-slow motion and therefore one of their normal life-cycles takes an enormous amount of *our* time. p.43

9. Who Is Moving, Anyway?
    - a. The relativity of motion is both key to understanding Einstein’s theory and a potential source of confusion.
    - b. moving [observers] are justified in proclaiming (from their perspective) they are motionless and that it is the stationary [observers who] are moving ... leading to the seemingly opposite conclusion that [stationary observers] are [living more slowly] compared with those [who are] moving.
    - c. ... [one is] forced by the basic reasoning of special relativity to give up the idea that everyone, regardless of state of motion, agrees about which events happen at the same time (the time difference depends on relative velocity p.44

10. Motion’s Effect on Space p.46
    - a. ... motion ... has an equally dramatic effect on space - i.e. observers perceive a moving object as being shortened along the direction of its motion (moving objects are shorter in the direction of motion) p.47







11. Motion through Spacetime
    a. The constancy of the speed of light replaces the traditional view of space and time as rigid and objective structures with a new conception in which they depend intimately on the relative motion between observer and observed.
    b. ... not only can spatial dimensions share an object's motion, but the *time* dimension can share this motion as well (i.e. *most* of an object's motion is through time, not space - [we move] through space ...and time) p.49
    c. ... mathematician Hermann Minkowski (and ultimately Einstein), advocated thinking about time as another [4th] dimension of the universe - in some ways quite similar to the three spatial dimensions.
    d. ... the notion of time as a dimension is actually concrete: when we want to meet someone, we tell them where "in space" [address/location]; equally important, *when* (i.e. where "in time" our meeting will take place) ...
    e. Events are specified by *four* pieces of information: three in space and one in time - the location of the event in space and in time, or in *spacetime* (in this sense, time is another dimension. p.50
    f. space and time are different examples of dimensions [so one] can speak of an object's speed through time in a manner resembling the concept of its speed through space.
    g. When an object moves through space relative to us, its clock runs slow compared to ours (the speed of its *motion through time slows down*).
    h. Einstein proclaimed that all objects in the universe are *always* traveling through spacetime at [the] fixed speed of light.
       NOTE: we are [accustomed] to the notion that objects travel at speeds considerably less than that of light
        (1) [in a generalized sense] an object's combined speed through *all four* dimensions - three space and one time - is equal to that of light.
        (2) one fixed speed can be shared between the different dimensions - different space *and* time dimensions.
        (3) If an object is sitting still (relative to us) and consequently does not move through space at all, then all of the object's motion is used to travel through one dimension - the time dimension.
        (4) all objects that are at rest relative to us and to each other move through time [and] age at exactly the same rate or speed.
        (5) If an object moves through space, some of the previous motion through time must be diverted (i.e. this sharing of motion implies that the object will travel more slowly through time than its stationary counterparts, since some of its motion is now being used to move through space - so its clock will tick more slowly if it moves through space).
        (6) ... time slows down when an object moves relative to [an observer] because this diverts some of its motion through time into motion through space.
    i. The speed of an object through space is merely a reflection of how much of its motion through time is diverted.
    j. ... there is a limit to an object's spatial velocity: the maximum speed through space occurs if *all* of an object's motion through time is diverted to motion through space (i.e. all light speed motion through time is diverted to light speed motion through space). p.51
    k. Something traveling at light speed through space will have no speed left for

motion through time (e.g. light does not get old: a photon that emerged from the Big Bang is the same age today as it was [back] then - there is no passage of time at light speed).

12. What about $E=mc^2$?
    a. Einstein's work showed that space and time, which had previously seemed to be separate and absolute, are actually interwoven and relative (as are other physical properties of the world)
    b. $E=mc^2$
        (1) the *energy (E)* of an object and its *mass (m)* are not independent concepts
        (2) its energy can be determined by multiplying its mass twice by *the speed of light* (c^2)
        (3) its mass can be determined by dividing its energy twice by the speed of light
        (4) a little mass goes an extremely long way in producing energy (e.g. conversion of less than 1% of 2 pounds of uranium into energy was used in the atomic bomb over Hiroshima)
    c. Einstein's equation gives a concrete explanation for the se fact that nothing can travel faster than light speed. p.52
    d. The faster something moves the more energy it has and from Einstein's formula the more energy something has the more massive it becomes [and] the more massive an object is, the harder it is to increase its speed.
    e. mass increases without limit as its speed approaches that of light [and] would require a push with an infinite amount of energy to reach or to cross the light barrier.
    f. [Such] is impossible and hence absolutely nothing can travel faster than the speed of light

B. Chapter Three: Of Warps and Ripples p.53
    1. Introduction
        a. Einstein realized that the dictum that nothing can outrun light was incompatible with Newton's universal theory of gravity - so, while resolving one conflict, special relativity gave rise to another.
        b. Einstein resolved the dilemma with his *general theory of relativity* - showing that space and time warp and distort to communicate the force of gravity.
    2. Newton's View of Gravity (His Universal Theory of Gravity) p.54
        a. [Newton] declared that absolutely everything exerts an attractive gravitational force on absolutely everything else .
        b. Based on a close study of Johannes Kepler's analysis of planetary motion, Newton deduced that the strength of the gravitational attraction between two bodies depends precisely on two things:
            (1) the amount of stuff/matter/mass composing each of the bodies
            (2) the distance between them
        c. Newton's universal theory of gravity asserts:
            (1) that the strength of attraction between two objects is larger for larger-mass objects and smaller for smaller-mass objects p.55
            (2) that the strength of attraction is larger for smaller separations between the objects and smaller for larger separations
            (3) that the gravitational force between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between them

d. Newton's theory [received] unequivocal support until the early part of the 20th century [when] Einstein's discovery of special relativity raised an insurmountable obstacle ....

3. The Incompatibility of Newtonian Gravity and Special Relativity
   - a. A central feature of special relativity is the absolute speed barrier set by light - a limit not only to material objects but also to signals and influences of any kind (although the world is full of ways for transmitting disturbances at *slower* than the speed of light).
   - b. Nothing outruns photons/light - i.e. no information can be transmitted faster than the speed of light (instantaneous transmission violates this precept) p.56
   - c. Einstein realized that Newton's theory of gravity conflicted with his special theory of relativity [so he] sought a new theory of gravity compatible with special relativity - and this ultimately led him to the discovery of *general relativity*, in which the character of space and time again went through a remarkable transformation.
4. Einstein's Happiest Thought
   - a. Newton's theory of gravity offered to no insight into what gravity is [or] how it actually works. p.57
   - b. special relativity implied [that] way Newton's theory was broken and its repair required coming to grips with the question of the true and full nature of gravity.
     - (1) [Contrary to individuals undergoing constant-velocity relative motion] what about individuals who experiencing *accelerated* motion? p.58
     - (2) observations [made by] such individuals will be more complicated to analyze [in order to bring] accelerated motion into [the] new-found understanding of space and time.
     - (3) Einstein's *"happiest thought"* showed how to do so.
   - c. Recognition that gravity and accelerated motion are interwoven is Einstein's key insight. p.60

     NOTE: WICK's RENDITION OF Greene's ILLUSTRATION:
     - (1) Gravity diminishes the farther objects or individuals are from one another
     - (2) But accelerated motion presses an object or individual against the floor or a seat
     - (3) Adjusting the rate of acceleration could balance out diminished gravity
     - (4) When the magnitudes of acceleration or gravity are judiciously adjusted, the force one feels from a gravitational field or from accelerated motion are indistinguishable.
   - d. Einstein called the indistinguishability between accelerated motion and gravity the *equivalence principle* (which plays a central role in general relativity). p.61
   - e. *general relativity* finishes the job initiated by *special relativity*
     - (1) Through its principle of relativity, the *special theory of relativity* declares a democracy of observational vantage points: the laws of physics appear identical to all observers undergoing constant-velocity motion but this excludes the viewpoints of individuals who are accelerating ...
     - (2) Since there is no difference between an accelerated vantage point *without* a gravitational field and a non-accelerated vantage point *with* a gravitational field, [one] can invoke the latter perspective and declare that *all observers, regardless of their state of motion, may proclaim that they are stationary and "the rest of the world is moving by them," so long as they include a suitable gravitational field in the description of their own*

surroundings.

f. ... through the inclusion of gravity, general relativity ensures that all possible observational vantage points are on equal footing (thus distinctions between observers that rely on accelerated motion admit an equivalent description without acceleration, but with gravity (cf. Chapter 2 above)

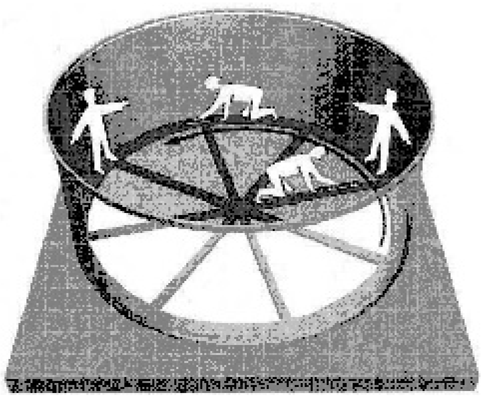
g. [The] deep connection between gravity and accelerated motion [made] Einstein happy [b/c while] gravity is mysterious, elusive and ethereal accelerated motion is concrete and tangible. By finding a fundamental link between the two, [he] could use [t]his understanding of motion as a powerful tool toward gaining a similar understanding of gravity - an approach that ultimately bore the fruit of *general relativity*.

5. Acceleration and the Warping of Space and Time p.62

a. An object is accelerating if either the speed or the direction of its motion changes.

b. For simplicity [Greene] focus[es] on accelerated motion in which *only* the direction of [an] object's motion changes while its speed stays fixed.

c. *Lorentz contraction:* the length of an object appears shortened along the direction of its motion p.63



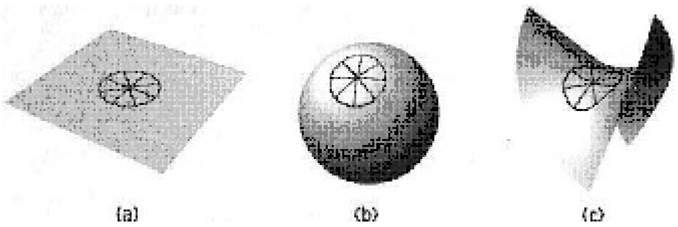
(1) measurements of the circumference of a spinning "Tornado Ride" at a County Fair will differ - the measuring ruler itself will be shorter when the ride is spinning than when it is stationary

(a) when at rest, per geometry, the ratio of circumference to radius is two times the number pi (2_{Π} or 3.14 X 2 = 6.28)

(b) but measurements of the radius perpendicular to the direction of the ride's motion remains the same (is not contracted) p.64

(2) calculating the ratio of the circumference of the ride to its radius when spinning one gets a number that is larger than two times pi ($>2_{\Pi}$ or > 3.14 X2) since the circumference is longer but the radius the same

(3) The ratio of two times pi (2_{Π} or 2 X 3.14) holds true for circles drawn on a flat surface but if a circle is drawn on a warped or curved surface, its usual spatial relationships will also be distorted (i.e. the ratio of its circumference to its radius will generally not be two times pi)
NOTE: a circle drawn on a sphere (b) has a shorter circumference than one drawn on a flat sheet of paper (a), while a circle drawn on the surface of a saddle (c) has a longer circumference, even though they all have the same radius p.65



- (a) the ratio of the circumference to the radius of the circle in (b) will be less than two times pi
- (b) the ratio of the circumference to the radius of the circle in (c) will be greater than two times pi

d. Einstein propose[d] the curving of space as an explanation for the violation of ordinary, Euclidean geometry.
  - (1) the familiar geometrical spatial relationships pertaining to "flat" space figures like a circle on a flat table, *do not hold* from the perspective of an accelerated observer.
  - (2) similarly, the warping of space, holds in all instances of accelerated motion.

e. accelerated motion results in a warping of space and an analogous warping of time (i.e. time is also affected since (cf. Chapter 2) *special relativity* articulates a union between space and time and knitting space and time together into the unified structure of space-time, special relativity declares, *"What's true for space is true for time."* p.66

f. What is meant by warped time?
  - (1) ILLUSTRATION:
    - (a) ... on the Tornado Ride, the farther out along a radial strut one is from the center, the farther one must travel to complete one rotation, and therefore the faster one must go.
    - (b) but from special relativity, the faster one goes, the slower one's watch ticks, and hence one's watch on the circumference will tick more slowly than one's watch on the radius
    - (c) the rate of passage of time depends upon one's precise position (in the case of the Tornado Ride, one's distance from the center of the ride)
  - (2) Time is warped if its rate of passage differs from one location to another.
  - (3) Greater acceleration is tied up with slower clocks - i.e. greater acceleration results in a more significant warping of time. p.67

g. Since [Einstein] had already shown gravity and accelerated motion to be effectively indistinguishable, and that accelerated motion is associated with the warping of space and time, he made the proposal: *gravity is the warping of space and time*.

6. The Basics of General Relativity

a. In Newtonian gravity the sun keeps the earth in orbit with an unidentified gravitational "tether" ...

b. Einstein provided a new conception of what actually happens: (SIMPLIFICATION)
  - (1) 1st, for the moment ignore time and focus solely on a visual model of space
  - (2) 2nd, reference will be made to a two-dimensional analog of three-dimensional space

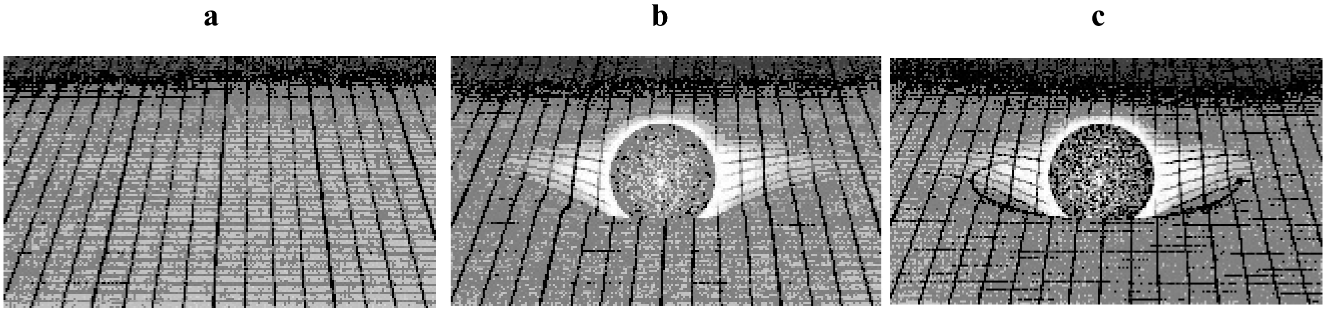
c. In the absence of any matter or energy, Einstein envisioned that space would be flat p.68

d. [But Einstein noted that] a massive body like the sun, and indeed any body, exerts a gravitational force on other objects.

  (1) as was noted earlier, gravitational forces are indistinguishable from accelerated motion

  (2) and a mathematical description of accelerated motion *requires* the relations of curved space

e. ... links between gravity, accelerated motion, and curved space led Einstein to [suggest] that the presence of mass, such as the sun, causes the fabric of space around it to warp.



f. the fabric of space becomes distorted due to the presence of a massive object

g. the shape of space responds to objects in the environment p.69

h. this warping affects other objects moving in the vicinity as they now must traverse the distorted spatial fabric

i. absent the presence of another object, a moving object will travel along a straight line (a)

j. given the presence of another object, a moving object will travel along a curved path (b) and perhaps even orbit that object (c)

k. Einstein specified the mechanism by which gravity is transmitted: the warping of space: the gravitational tether holding the earth in orbit is the warping of the spatial fabric caused by the sun's presence. p.70

l. two essential features of gravity:

  (1) 1st, the more massive the object, the greater the distortion it causes in the surrounding space (the more massive the object, the greater the gravitational influence it can exert on other bodies)

  (2) 2nd, the amount of spatial warping due to a massive body decreases as distance from it increases

m. all objects warp space - even if slight or minuscule p.71

7. A Few Caveats (Comment: the membrane analogy (above) is [valuable but] not perfect and has some shortcoming)

  a. 1st, when the sun causes the fabric of space around it to warp this is not due to its being pulled downward by gravity

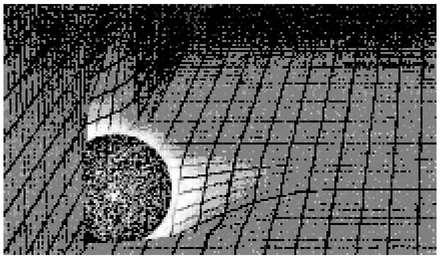
    (1) Einstein taught that the warping of space is gravity (i.e. the mere presence of an object with mass causes space to warp).

    (2) Einstein showed that objects move through spacetime along the shortest possible paths - the "easiest possible paths" or the "paths of least resistance."

    (3) If space is warped, such paths will be curved [but] the physical mechanism by which these distortions occur expresses a reformulation of

gravity in terms of curved space.

b. 2nd, the fabric of space is not two-dimensional p.72



  (1) objects warp the three-dimensional space surrounding them (
  (2) all of the space surrounding an object is distorted
  (3) space is the medium by which the gravitational force is communicated
  (4) John Wheeler re: gravity says, *“mass grips space by telling it how to curve, space grips mass by telling it how to move.”*

c. 3rd, the time dimension is suppressed

  (1) special relativity requires that the time dimension be placed on a par with the three familiar spatial dimensions (even though it is significantly harder to “see” time) p.73
  (2) acceleration, and hence gravity, warps both space and time (cf. the Tornado Ride illustration above)

8. Conflict Resolution

  a. Einstein’s introduction of space and time as dynamic players provided a clear conceptual image of how gravity works and resolves the conflict with special relativity that afflicts Newton’s theory of gravity.
  b. When no mass is present, space is flat, and a small object will be at rest or will travel at a constant velocity
  c. Given the introduction of a large mass, space will warp - however, the distortion will not be instantaneous, rather, it will spread outward from the massive body, ultimately settling down into a warped shape that communicates the gravitational pull of the new body.
  d. Einstein calculated that disturbances to the fabric of the universe travel at *precisely the speed of light* (i.e. gravitational disturbances keep pace with, but do not outrun, photons). p.74

9. The Warping of Time, Revisited

  a. A warp distorts the shape of space (“warped space”).
  b. The meaning of “warped time” [is] more difficult to decipher ...
  c. The warping of time predicted by general relativity implies that [a] clock will run slower and slower as the gravitational field get stronger and stronger (i.e. gravity distorts time as well as space). p.75
  REVIEW: feeling accelerated motion is the same as feeling gravitational force
  d. Stronger gravitational fields, such as those just outside a black hole cause the flow of time to slow even further (stronger gravitational fields cause a more severe warping of time).

10. Experimental Verification of General Relativity

  a. ... allowing space and the time to curve, warp, and ripple results is what [is] commonly refer[red] to as gravity. p.76
  b. The motivation for questioning [Newton’s theory of gravity] was its property of instantaneous transmission of the gravitational force, in conflict with *special relativity*.
  c. Einstein’s General Relativity predicts that the sun will cause the surrounding space and time to warp and such distortion *will influence the path taken by the starlight.* p.77

(1) photons of distant origin travel along the fabric of the universe [and] if the fabric is warped, the motion of the photons will be affected much as for a material body.

(2) The bending of the path of light is greatest for those light signals that just graze the sun on their way to earth [and] the bending of the starlight's path results in a shift in the *apparent* position of the star.

d. The predictions of general relativity have been uniformly confirmed - Einstein's description of gravity is not only compatible with special relativity, but yields predictions closer to experimental results than those of Newton's theory. p.78

11. Black Holes, the Big Bang, and the Expansion of Space

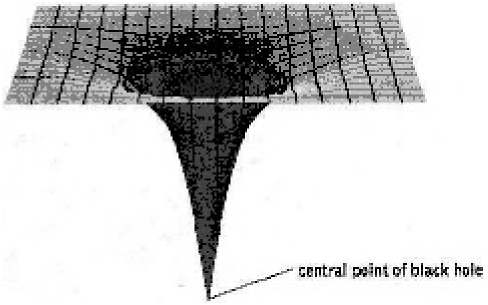
a. Whereas special relativity is most manifest when things are moving fast, general relativity comes into its own when things are very massive and the warps in space and time are correspondingly severe.

b. Two examples:

(1) 1st, "black holes"

(a) German astronomer Karl Schwarzschild use[d Einstein's revelations on gravity] to understand the way space and the time warp in the vicinity of a perfectly spherical star.

(b) *Schwarzschild's solution"* showed that if the mass of a star is concentrated in a small enough spherical region, so that its mass divided by its radius exceeds a particular critical value, the resulting spacetime warp is so radical that *anything*, including light, that gets too close to the star will be unable to escape its gravitational grip. p.79



i) initially called *dark* or *frozen stars*, years later John Wheeler coined the term *black holes*

ii) *black* because they cannot emit light and *holes* because anything getting too close falls into them, never to return

(c) objects that pass by black holes at a "safe" distance are deflected in much the same way that they would be by an ordinary star

(d) objects that get closer than the black hole's *event horizon* are doomed - subject to an ever-increasing and ultimately destructive gravitational strain (tearing objects to shreds)

(e) black holes have such strong gravitational fields [that] passage through time would slow *way down* (a kind of time machine)p.80

(f) since they are black, [black holes] cannot be observed by directly scanning the sky with telescopes (i.e. astronomers search for black holes by seeking anomalous behavior of other more ordinary light-emitting stars that may be positioned just outside a black hole's *event horizon).*

(2) 2nd, the origin and evolution of the whole universe p.81

(a) space and the time respond to the presence of mass and energy [and] this distortion of spacetime affects the motion of other cosmic bodies moving in the vicinity of the resulting warps

(b) the precise way in which these bodies move, by virtue of their own mass and energy, has a further affect on the warping of spacetime, which further affects the motion of the bodies, and on and on the interconnected cosmic dance goes

(c) through the equations of general relativity Einstein described the mutual evolution of space, time, and matter quantitatively and concluded: the overall size of the spatial universe must be changing in time (i.e. either the fabric of the universe is stretching or it is shrinking, but it is not simply staying put). p.82

i) but the notion of an always existing, never-changing universe was too ingrained for even [Einstein] to abandon

ii) [so he] modified his equations by introducing something known as a *cosmological constant* - to avoid this prediction and bask in the comfort of a static universe

iii) through detailed measurements of distant galaxies, American astronomer Edwin Hubble experimentally established that the universe is *expanding*

iv) Einstein cited his modification to the original form of his equations as the biggest blunder of his life

v) In the early 1920s Russian meteorologist Alexander Friedmann had used Einstein's original equations to show that all galaxies would be carried along on the substrate of stretching spatial fabric, thereby speedily moving away from all others

vi) in reverse, the fabric of space shrinks [and] the matter making up *everything* is squeezed by a cosmic vise to astounding density - a point in which all matter and energy is squeezed together to unimaginable density and temperature. p.83

vii) in the Big Bang, there is no surrounding space ...

12. Is *General Relativity* Right?

a. No deviations from the predictions of general relativity have been found in experiments performed with our present level of technology.

b. *General relativity* appears to be fundamentally incompatible with another extremely well-tested theory: *quantum mechanics*.

(1) the conflict prevents physicists from understanding what really happens to space, time, and matter when crushed together fully at the moment of the Big Bang or at the central point of a black hole.

(2) the conflict [evidences] a fundamental deficiency in [the] conception of nature

c. Resolution of this conflict is the central problem of modern theoretical physics.

C. Chapter Four: Microscopic Weirdness p.85

1. The Quantum Framework p.86

a. Quantum mechanics is a conceptual framework for understanding the microscopic properties of the universe.

b. those who use quantum mechanics follow rules and formulas laid down by the "founding fathers" of the theory without really understanding *why* the procedures work or *what* they really mean. p.87

c. but quantum mechanics shows that a number of basic concepts essential to understanding the familiar world *fail to have any meaning* when [the] focus narrows to the microscopic realm (on atomic and subatomic scales). p.88

d. Two observations:

(1) 1st, beyond the fact that it is a mathematically coherent theory, the only reason [to] believe in quantum mechanics is because it yields predictions that have been verified to astounding accuracy.

(2) 2nd, quantum mechanics seems bizarre or ludicrous

2. It's Too Hot in the Kitchen (the road to quantum mechanics begins w/a puzzling problem)

NOTE: even by taking all the air out of an oven before heating it up, it will still generate waves of radiation in its interior

a. electromagnetic waves carry energy

b. using well-established calculational procedures physicists came up with a ridiculous answer for any chosen temperature, the total energy in the oven is *infinite* - but is this was nonsense: an *infinite* amount of energy?

c. When Maxwell's electromagnetic theory is applied to the radiation in an oven it shows that the waves generated by the hot walls must have a whole number of peaks and troughs that fit perfectly between opposite surfaces.

(1) *wavelength* is the distance between successive peaks or successive troughs of the waves p.89

(2) *frequency* refers to the number of up and down cycles of oscillation that a wave completes every second

(a) frequency is determined by the wavelength

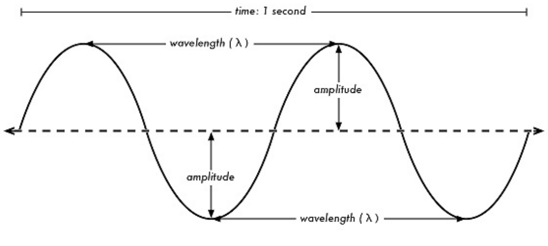
(b) wavelength is determined by the frequency

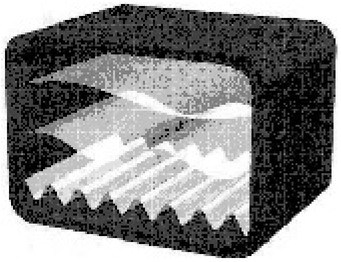
(c) longer wavelengths imply lower frequency

(d) shorter wavelengths imply higher frequency

(3) *amplitude* describes the maximum height or depths of a wave

d. more energy corresponds to a larger amplitude while less energy corresponds to a smaller amplitude





(1) each of the allowed waves (*regardless of its wavelength*) carries the same amount of energy with the precise amount determined by the temperature of the oven

(2) all of the possible wave patterns within the oven are on completely equal footing when it comes to the amount of energy they embody p.90

(3) this spells the downfall of classical physics for even though requiring that all waves have a whole number of peaks and troughs rules out an

enormous variety of conceivable wave patterns in the oven, there are still an infinite number that are possible - those with even more peaks and troughs.

(4) since each wave pattern carries the same amount of energy an infinite number of them translates into an infinite amount of energy

3. Making Lumps at the Turn of the Century p.91
    a. Max Planck reduced the result of infinite energy in an oven to one that is finite and guessed that energy carried by electromagnetic wave comes in lumps p.92
    b. the energy can be 1X some fundamental "energy denomination," or 2X it, or 3X it but that's it - when it comes to energy no fractions are allowed
    c. Planck suggested that the energy denomination of a wave (the minimal lump of energy that it can have) is determined by its frequency.
    NOTE: the *minimum* energy a wave can have is *proportional to its frequency*
        (1) larger frequency (shorter wavelength) implies larger minimum energy
        (2) smaller frequency (longer wavelength) implies smaller minimum energy
        (3) long-wavelength radiation is intrinsically less energetic than short-wavelength radiation (IL: gentle ocean waves are long and luxurious while harsh ones are short and choppy)
    d. Planck's calculations showed that this lumpiness of the allowed energy in each wave [answered] the previous ridiculous result of infinite total energy
    e. When an oven is heated to some chosen temperature, the calculations based on 19th-century thermodynamics predicted the common energy that each and every wave would supposedly contribute to the total.
    f. But if the minimum energy a particular wave can carry exceeds the energy it is supposed to contribute, it can't contribute and instead lies dormant.
    g. Since, according to Planck, the minimum energy a wave can carry is proportional to its frequency, as [one] examine[s] waves in the oven of ever larger frequency (shorter wavelength), sooner or later the minimum energy they can carry is bigger than the expected energy contribution.
        (1) these waves with ever larger frequencies cannot contribute the amount of energy demanded by 19th century physics p.93
        (2) so only a finite number of waves are able to contribute to the oven's total energy - leading to a finite amount of total energy
        (3) the lumpiness of the fundamental units [of energy] and the ever increasing size of these lumps as [one] go[es] to higher frequencies ... changes an infinite answer to one that is finite
    h. Planck's finite answer for the energy agreed with experimental measurements.
    i. Planck found that by adjusting *one* parameter that entered into his new calculations, he could predict accurately the measured energy of an oven for any selected temperature.
    j. This one parameter is the proportionality factor between the frequency of a wave and the minimal lump of energy it can have.
    k. *Planck's constant (denoted as an "h" having a line through it)* is about a billionth of a billionth of a billionth in everyday units $\hbar$
    l. According to Planck's assertion, the size of these jumps in energy grows as the frequency of the waves gets higher and higher (while wavelengths get shorter and shorter). This is the crucial ingredient that resolves the infinite-energy paradox.
    m. The smallness of *Planck's constant* confines most of these radical departures

from life-as-usual to the microscopic realm.

4. What are the Lumps? p.94
    - a. Planck had no justification for his pivotal introduction of lumpy energy.
    - b. Einstein found an explanation for this insight by puzzling over the *photoelectric effect.*
        - (1) 887 German physicist Heinrich Hertz found that when electromagnetic radiation (light) shines on certain metals, they emit electrons.
        - (2) metals have the property that some of their electrons are only loosely bound within atoms [so] when light strikes a metallic surface it relinquishes energy
        - (3) as the intensity of light (brightness) is increased the speed of ejected electrons does not increase; rather, the number of ejected electrons increases but their speed stays fixed.
        - (4) the speed of the ejected electrons increases if the *frequency* of the impinging light is increased
        - (5) the speed of ejected electrons decreases if the *frequency* of the light is decreased and as the frequency of light used is decreased, there comes a point when the speed of the emitted electrons drops to zero and they stop being ejected from the surface, *regardless of the possibly blinding intensity of the light source.* p.95
    - c. Einstein suggested incorporating Planck's lumpy picture of wave energy into a new description of light.
    - d. [Einstein] proposed that a light beam should be thought of as a stream of tiny packets/particles of light (dubbed "*photons*" by chemist Gilbert Lewis) p.96
    - e. Einstein suggested [that] a microscopic mechanism underlies the photoelectric effect: an electron is knocked off a metallic surface if it gets hit by a sufficiently energetic photon (the energy of each proton being proportional to the frequency of the light wave)
        - (1) the electrons in a metal must be jostled by a photon possessing a certain minimum energy in order to be kicked off the surface
        - (2) no electrons are jostled free regardless of the huge total energy embodied in the impinging light beam if its frequency (and thus the energy of its individual photons) is too low
        - (3) electrons will be knocked off the surface as soon as the frequency of light shone on them gets high enough
        - (4) the total intensity of a light beam of a chosen frequency is increased by increasing the number of photons it contains
        - (5) more photons result in more electrons being hit and knocked clear off the surface
        - (6) the leftover energy that each electron has after ripping free depends solely on the energy of the photon that hits it and this is determined by the frequency of the light beam, not its total intensity
        - (7) for electrons to leave the surface with greater speed the frequency of the impinging light beam (the energy denomination of the photons) must be increased p.97
    - f. Einstein showed that Planck's guess of lumpy energy ... reflects a fundamental feature of electromagnetic waves: they are composed of particles (photons) that are little bundles (or *"quanta:")* of light

5. Is It a Wave or Is It a Particle?

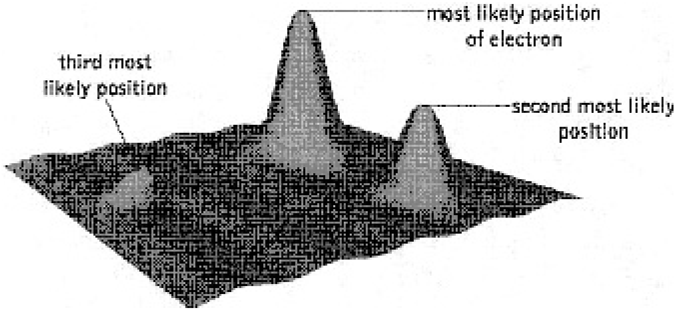
a. Just as water (and water waves) are composed of a huge number of water molecules so too light waves are composed of a huge number of particles (*"photons"*)

b. Newton proclaimed that light consisted of a stream of particles but some of his colleagues (e.g. Christian Huygens) argued that light is a wave
NOTE: experiments carried out by English physicist Thomas Young in the early 1800s showed that Newton was wrong

c. Somehow *photons*, although they are particles, *embody wavelike features of light* as well. p.102
  (1) The energy of these particles is determined by a wavelike feature - *frequency*.
  (2) But ... light [also] has particle properties. p.103
  (3) ... [so] light has both wave-like and particle-like properties, i.e. *"wave-particle duality."*

6. Matter Particles Are Also Waves
  a. 1923 French nobleman Prince Louis de Broglie suggested that the wave-particle duality applied not only to light but to matter as well.
    (1) that [since] Einstein's $E=mc^2$ relates mass to energy, that [since] Planck and Einstein related energy to the frequency of waves, [that] therefore, by combining the two, mass should have a wave-like incarnation as well p.104
    (2) [that] an electron, normally thought of as being a particle, might have an equally valid description in terms of waves
  b. (mid-1920s) proof came from the work of Clinton Davisson and Lester Germer
    (1) electrons [were found to] exhibit *interference phenomena* - the telltale sign of *waves*.
    (2) electrons embody wave-like character in conjunction with their more familiar depictions as particles
  c. similar experiments lead to the conclusion that all matter has a wavelike character
    (1) how does this jibe with real-world experience of matter as being solid and sturdy and in no way wave-like? p.105
    (2) de Broglie set down a formula for the wavelength of matter waves, and it shows that the wavelength is proportional to Planck's constant $\hbar$ (more precisely, the wavelength is given by Planck's constant divided by the material body's momentum)
    (3) since Planck's constant is so small, the resulting wavelengths are similarly minuscule compared with everyday scales - that is why the wavelike character of matter becomes directly apparent only upon careful microscopic investigation. $\hbar$

7. Waves of What?
  a. 1926 German physicist Max Born refined Erwin Schrodinger's interpretation of an electron wave asserting that an electron wave must be interpreted from the standpoint of *probability*.
    (1) places where the square of magnitude of the wave is *large* are places where the electron is more *likely* to be found
    (2) places where the magnitude is *small* are places where the electron is *less likely* to be found



b. Quantum mechanics injects the concept of probability into the universe at a ... [deep] level. p.106

(1) The wave nature of matter implies that matter itself must be described fundamentally in a probabilistic manner.

(2) ... at a microscopic level ... the best [one] can ever do is say that an electron has a particular probability of being found at any given location.

c. The probabilistic interpretation has the virtue that if an electron wave does what other waves can do (for instance, slam into some obstacle and develop all sorts of distinct ripples) it does not mean that the electron itself has shattered into separate pieces. Rather, it means that there are now a number of locations where the electron might be found with a non-negligible probability. p.107

(1) the number of times an electron is found at any given location is governed by the shape of the electron's *probability wave*

(2) *probability waves* came to be known as *wave functions*

d. According to *quantum mechanics*, the universe evolves according to a rigorous and precise mathematical formalism [which] determines only the probability that any particular future will happen - not which future actually ensues.

e. debate about what quantum mechanics really means continues [but] no matter how [one] interpret[s] quantum mechanics, it shows that the universe is founded on principles that from the standpoint of [daily] experiences are bizarre. p.108

8. Feynman's Perspective

a. theoretical physicist Richard Feynman offered a new way of thinking about the probabilistic core of quantum mechanics

(1) electrons are little wisps of matter p.109

(2) photons that bounce off an electron affect its subsequent motion

b. Feynman's *"sum-over-paths"* approach to quantum mechanics [states that]: each individual electron actually *traverses every possible trajectory simultaneously* (it simultaneously "sniffs" out every possible path connecting its starting location with its final destination). p.110

(1) no probability wave needs to be associated with the electron p.111

(2) instead, (more bizarre) the probability that the electron (always viewed as a particle) arrives at any chosen point is built up from the combined effect of every possible way of getting there.

(3) QUESTION W/O ADEQUATE ANSWER: how can one electron simultaneously take different paths (and no less than an infinite number of them?

c. Feynman showed that if [one] examine[s] the motion of large objects (large compared to subatomic particles) all paths but one cancel each other out when their contributions are combined - i.e. only one of the infinity of paths matters as far as the motion of the object is concerned.(and this trajectory is precisely the one emerging from Newton's laws of motion)

(1) this is why in the everyday world it seems that objects follow a single, unique, and predictable trajectory from their origin to their destination.

(2) but for microscopic objects many different paths can and often do contribute to an object's motion.

9. Quantum Weirdness p.112

a. *the uncertainty principle* fundamentally differentiates quantum from classic reasoning (discovered by the German physicist Werner Heisenberg in 1927)

(1) by turning down the intensity of the light source [one] decreas[es] the number of photons it emits p.113

(2) once [one] get[s] down to emitting individual photons [one] cannot dim the light any further without actually turning it off

(3) hence, there is always a minimal disruption that [one] cause[s] to the electrons velocity through measurement of its position

(a) such is almost correct

(b) Planck's law indicates that the energy of a single proton is proportional to its frequency (inversely proportional to its wavelength)

(c) when one bounces a wave off an object, the information received is only enough to determine the object's position to within a *margin of error equal to the wave's wavelength*

(d) by examining how wave cycles are disrupted one can determine (to within a margin of error equal to the length of the wave cycles) the location of an object

(e) a photon can be used to pinpoint an object's location only to within a precision of one wavelength

(f) a high frequency (short wavelength) light can be used to locate an electron with greater precision, but high-frequency protons are very energetic and sharply disturb the electron's velocity

(g) a low-frequency (long wavelength) light can be used to locate an electron with less precision, minimally impacting the electron's motion

(4) Heisenberg found a mathematical relationship b/tw the precision w/wh one measures the electron's position and the precision w/wh one measures its velocity: each is inversely proportional to the other p.114

(a) greater precision in a position measurement necessarily entails greater imprecision in a velocity measurement

(b) greater precision in a velocity measurement necessarily entails greater imprecision in a position measurement

(5) Heisenberg showed that the trade-off between the precision of position and velocity measurements is a fundamental fact that holds true regardless of the equipment used for the procedure employed

(6) quantum mechanics shows that at a microscopic level [one] *cannot possibly know both of these features with total precision* (the more precisely one knows one the less precisely one knows the other)

(a) this applies not only to electrons but to all constituents of nature

(b) electrons, and everything else for that matter, cannot be described as simultaneously being at such-and-such location *and* having such-and-such speed (nature does not allow [these] constituents to be “cornered”

- b. The *uncertainty principle* gives rise to a striking effect known as *quantum tunneling.* p.115
  - (1) at the level of fundamental particles, quantum mechanics shows that the wave functions/probability waves of particles do not all bounce off an encountered object but may have a tiny piece that *spills out* through an encountered object actually penetrating and emerging on the other side
    - (a) Heisenberg also showed that there is a trade-off in the precision of *energy* measurement and *how long* one takes to do the measurement (quantum mechanics asserts that one can’t say that a particle has precisely such-and-such energy at precisely such-and-such a moment in time).
    - (b) quantum mechanics allows a particle to borrow energy so long as it can relinquish it within a time frame determined by Heisenberg’s Uncertainty Principle
    - (c) For microscopic particles facing a concrete slab, they can and sometimes do borrow enough energy to do what is impossible from the standpoint of classical physics - momentarily penetrate and tunnel through a region that they do not initially have enough energy to enter. p.116
  - (2) The probability rules of quantum mechanics, and, in particular, the actual smallness of the Planck constant in the real world, show that if one walked into a solid wall every second, one would have to wait longer than the current age of the universe to have a good chance of passing through it on one attempt [but] with eternal patience and longevity one could, sooner or later, emerge on the other side
- c. The uncertainty principle captures the heart of quantum mechanics - i.e. features normally thought of as being so basic as to be beyond question (e.g. that objects have definite positions and speeds and that they have definite energies at definite moments) are now seen as mere artifacts of Planck’s constant being so tiny on the scales of the everyday world.

- D. Chapter Five: The Need for a New Theory: General Relativity vs. Quantum Mechanics p.117
  - 1. Introduction
    - a. Since their usual domains of applicability are so different, most situations require the use of quantum mechanics *or* general relativity, but not both.
    - b. Where things are very massive and very small (e.g. near the central point of black holes or the whole universe at the moment of the Big Bang) both general relativity and quantum mechanics [are required] for proper understanding ... but ... their union brings violent catastrophe. p.118
    - c. Well-formulated physical problems elicit nonsensical answers when the equations of both these theories are co-mingled (often a prediction that the quantum mechanical probability for some process is not [some] percent[age] but *infinity).*
  - 2. The Heart of Quantum Mechanics
    - a. Heisenberg’s uncertainty principle shows that the universe is a frenetic place when examined on smaller and smaller distances/shorter and shorter time scales.
      - (1) inability to know both the positions and velocities of elementary particles implies that the microscopic realm is intrinsically turbulent.
      - (2) Even without “direct hits” from an experimenter’s disruptive photon, the

electron's velocity severely and unpredictably changes from one moment to the next. p.119

- (3) Even in the most quiescent setting imaginable, such as an empty region of space, the uncertainty principle tells us that from a microscopic vantage point there is a tremendous amount of activity. And this activity gets increasingly agitated on ever smaller distance and time scales.
- (4) quantum accounting is essential to understand this:
  - (a) a particle (such as an electron) can temporarily borrow energy to overcome a literal physical barrier
  - (b) the shorter the time for which energy can be lent, the larger the amount the particle seeks
  - (c) the amount "borrowed" at any moment goes through extreme fluctuations

- b. Heisenberg's uncertainty principle asserts that frantic shifting back and forth of energy and momentum is occurring perpetually in the universe on microscopic distance and time intervals.
  - (1) Even in an empty region of space the uncertainty principle says that the energy and momentum are *uncertain* (fluctuating between extremes, constantly extracting "loans"from the universe and subsequently "paying"them back).
  - (2) Even in a quiet empty region of space everything participates in these exchanges. p.120
    - (a) energy (and momentum as well) is the ultimate convertible currency
    - (b) $E=mc^2$ [demonstrates] that energy can be turned into matter and vice versa
  - (3) Quantum-mechanical uncertainty [shows that] the universe is a teeming, chaotic, frenzied arena on microscopic scales
  - (4) Since the borrowing and repaying on average cancel each other out, an empty region of space looks calm and placid when examined with all but microscopic precision.
- c. [Heisenberg's] uncertainty principle ... reveals that macroscopic averaging obscures a wealth of microscopic activity (this frenzy is *the* obstacle to merging general relativity and quantum mechanics)

3. Quantum Field Theory
   - a. Introduction
     - (1) Schrodinger's *quantum wave equation* was only an approximate description of microscopic physics - his mathematical framework/formation of quantum mechanics encompassing the experimentally discovered wave-particle duality did not incorporate special relativity. p.121
     - (2) But special relativity is central to a proper quantum-mechanical framework
     - (3) The microscopic frenzy requires recognition that energy can manifest itself in a huge variety of ways - a notion that comes from the special relativistic declaration $E=mc^2$.
     - (4) Schrodinger's approach ignored the malleability of matter, energy, and motion.
   - b. Physicists focused their initial efforts to merge special relativity with quantum

concepts on the electromagnetic force and its interactions with matter.

(1) physicists created *quantum electrodynamics (a relativistic quantum field theory,* or *a quantum field theory)*

(a) *quantum* b/c all of the probabilistic and uncertainty issues are incorporated from the outset

(b) *a field theory* b/c it merges the quantum principles into the previous classical notion of a force field - in this case Maxwell's electromagnetic field

(c) *relativistic* b/c special relativity is also incorporated

(2) *quantum electrodynamics* is arguably the most precise theory of natural phenomena ever advanced

(3) Through *quantum electrodynamics*, physicists have been able to solidify the role of photons as the "smallest possible bundles of light" and to reveal their interactions with electrically charged particles such as electrons, in a mathematically complete, predictive, and convincing framework. p.122

c. Physicists, in analogy with *quantum electrodynamics*, were able to construct quantum field theories for the strong and the weak forces, called *quantum chromodynamics* ("quantum strong dynamics") and *quantum electroweak theory*.

(1) Sheldon Glashow, Abdus Salam, and Steven Weinberg that the weak and electromagnetic forces are naturally *united* by their quantum field-theoretic description even though their manifestations seem to be utterly distinct in the world around us.

(a) weak force fields diminish to almost a vanishing strength on all but subatomic distance scales

(b) electromagnetic fields have an indisputable macroscopic presence

(2) at high enough energy and temperature (e.g. a mere fraction of the second after the Big Bang) electromagnetic and weak forces *dissolve* into one another, take on indistinguishable characteristics, and are more accurately called *electroweak* fields.

(3) When the temperature drops, as it has done steadily since the Big Bang, the electromagnetic and weak forces *crystallize* out in a different manner from their common high temperature form, through a process known as *symmetry breaking*, and therefore appear to be distinct in the cold universe ... p.123

d. By the 1970s physicists had developed *"the standard theory"* or *"standard model"* of particle physics - a sensible and successive quantum-mechanical description of three of the four forces (strong, weak, electromagnetic) and had shown that two of the three non-gravitational forces (weak and electromagnetic) actually share a common origin (the electroweak force).

4. Messenger Particles

NOTE: according to the *"standard model"* ... p.124

a. the smallest constituent of an electromagnetic field are *photons* (wh/are sometimes referred to as the messenger particles for the electromagnetic force)

b. the smallest bundles of the strong force are *gluons* (wh/are the message particles for the strong nuclear force)

c. the smallest bundles of the weak force are *weak gauge bosons* (wh/are the message particles for the weak nuclear force)

d. these force particles have no internal structure - they are as elementary as the particles in the three families of matter

e. these force particles (photons, gluons, and weak gauge bosons) provide the microscopic mechanism for transmitting the forces they constitute

5. Gauge Symmetry
    a. gravity has been “the odd man out” thus far in discussion of the quantum theory of the forces of nature
    b. one might presume that physicists should seek a quantum field theory of the gravitational force with *gravitons* being both the smallest bundle of the gravitational force field (and the message particles for gravity) - but such has not yet been successfully accomplished (see #6 below: General Relativity vs. Quantum Mechanics) p.125
    c. gravitational force [places] all observers, regardless of the state of motion, on absolutely equal footing
        (1) observers thought of as accelerating may claim to be at rest - attributing the force they feel to being immersed in a gravitational field
        (2) in this sense, gravity enforces symmetry (ensures the equal validity of all possible observational points of view/all possible frames of reference)
    d. strong, weak, and electromagnetic forces also are all connected with enforcing symmetry
    e. just as the symmetry between all possible observational vantage points in general relativity requires the existence of the gravitational force, gauge symmetries require the existence of yet other forces p.126
    f. certain kinds of force fields provide appropriate compensation for shifts in force charges, thereby keeping the physical interactions between the particles completely unchanged
    g. all four forces (gravitational, strong, weak, and electromagnetic) are directly associated with principles of symmetry.
    h. a quantum field theory of the gravitational force has been elusive (see #6 below)
6. General Relativity vs. Quantum Mechanics p.127
    a. The usual realm of applicability of general relativity is that of large, astronomical distance scales.
    b. merging general relativity with quantum mechanics [requires] examining the microscopic properties/spatial fabric of space.
    c. *Everything* (even the gravitational field) is subject to the quantum fluctuations inherent in *the uncertainty principle*
    d. Although classical reasoning implies that empty space has zero gravitational field, quantum mechanics shows that *on average it is zero*, but that its actual value undulates up and down due to quantum fluctuations.
    e. The uncertainty principle [indicates] that the size of the undulations of the gravitational field gets larger as [one] focus[es] attention on smaller regions of space - i.e. narrowing the spatial focus leads to ever larger undulations.
    f. As gravitational fields are reflected by curvature, these quantum fluctuations manifest themselves as increasingly violent distortions of the surrounding space.
    g. probing to even smaller distance scales the random quantum mechanical undulations in the gravitational field correspond to such severe warping of space that it no longer resembles a gently curving geometrical object [but], rather takes on [a] frothing, turbulent, twisted form (coined *quantum foam* by John Wheeler)
    h. *The notion of a smooth spatial geometry, the central principle of general relativity, is destroyed by the violent fluctuations of the quantum world on short*

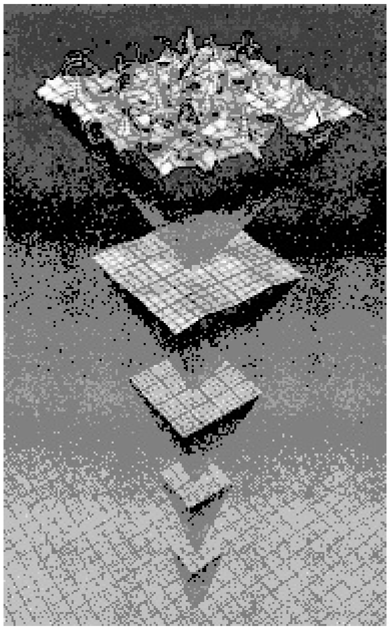
distance scales. p.129

i. On ultramicroscopic scales, the central feature of quantum mechanics (*the uncertainty principle)* is in direct conflict with the central feature of general relativity (the smooth geometrical model of spacetime).

j. ... this conflict rears its head in a very concrete manner: calculations that merge the equations of general relativity and those of quantum mechanics typically yield one and the same ridiculous answer - infinity.

k. the equations of general relativity cannot handle the roiling frenzy of *quantum foam*

l. [but] reced[ing] to more ordinary distances, the random, violent small-scale undulations cancel each other out and the concept of a smooth geometry for the fabric of the universe once again becomes accurate (like looking at a dot matrix picture at from a distance)



m. The fabric of spacetime appears to be smooth except when examined with ultra microscopic precision.

n. General relativity works on large enough distance (and time) scales but is rendered inconsistent on short distance (and time) scales.
NOTE: The top or fifth level in the diagram to the right represents the [incredibly small] *Planck length:* 1 millionth of 1 billionth of 1 billionth of 1 billionth of a centimeter (10^{-33} centimeter)p.130

o. [some] physicists are deeply unsettled by the fact that the two foundational pillars of physics as we know it are at their core fundamentally incompatible (an essential flaw in our understanding of the physical universe?)

p. Is there a logically sound theory be found to avoid the conflict - SUPERSTRING THEORY! (?) p.131

IV. Part Three: The Cosmic Symphony p.133

A. Chapter Six: Nothing but Music: The Essentials of *Superstring Theory* p.135

1. Introduction

a. With the discovery of *superstring theory*, musical metaphors take on a startling reality, for the theory suggests that the microscopic landscape is suffused with tiny strings whose vibrational patterns orchestrate the evolution of the cosmos.

(1) By contrast, the standard model views the elementary constituents of the universe as point-like ingredients with no internal structure.

(2) the standard model cannot be a complete or final theory because it does not include gravity [and] attempts to incorporate gravity into its quantum-mechanical framework have failed due to the violent fluctuations in the spatial fabric that appear at ultra microscopic distances (i.e. distances shorter than the Planck length).

b. 1984 physicists Michael Green and John Schwarz provided the first piece of convincing evidence that *superstring theory* (or *string theory*, for short) might well provide this understanding. p.136

c. *String theory* alters Einstein's general relativity in just the right way to make it fully compatible with the laws of quantum mechanics.

- d. Overview to *String Theory*
  - (1) The elementary ingredients of the universe are *not* point particles.
  - (2) The elementary ingredients of the universe are tiny, one-dimensional filaments somewhat like infinitely thin rubber bands, vibrating to and fro.
  - (3) The elementary ingredients of the universe are ultramicroscopic and make up the particles out of which atoms themselves are made.
  - (4) The elementary ingredients of the universe (the strings of string theory) are so small (on average about as long as the Planck length) that they appear point-like even when examined with our most powerful equipment.
  - (5) replacement of point particles with strands of string as the fundamental ingredients of everything has far-reaching consequences
    - (a) 1st, string theory appears to resolve the conflict between general relativity and quantum mechanics
      NOTE: the spatially extended nature of a string is the crucial new element allowing for a single harmonious framework incorporating both theories (general relativity and quantum mechanics)
    - (b) 2nd, string theory provides a unified theory, since all matter and all forces are proposed to arise from one basic ingredient: *oscillating strings*
    - (c) 3rd, string theory radically changes the understanding of spacetime

2. A Brief History of String Theory
   - a. 1968 theoretical physicist Gabriele Veneziano [sought] to make sense of observed properties of the strong nuclear force [and] realized that an esoteric formula concocted by Swiss mathematician Leonhard Euler (the so-called *Euler beta-function*) seemed to describe numerous properties of strongly interacting particles in one fell swoop. p.137
     - (1) Veneziano's observation provided a powerful mathematical encapsulation of many features of the strong force and it launched an intensive flurry of research aimed at using Euler's beta-function, and various generalizations, to describe the surfeit of data being collected at various atom smashers around the world.
     - (2) Euler's beta-function was a formula in search of an explanation - it seemed to work, but no one knew why.
   - b. 1970 the work of Yoichiro Nambu, Holger Nielsen and Leonard Susskind revealed the hitherto-unknown physics lurking behind Euler's formula.
     - (1) These physicists showed that if one modeled elementary particles as little, vibrating, one-dimensional strings, their nuclear interactions could be described exactly by Euler's function.
     - (2) If the pieces of string were small enough, they reasoned, they would still look like point-particles, and, hence, could be consistent with experimental observations.
     - (3) the string description of the strong force was shown to fail (high-energy experiments capable of probing the subatomic world showed that the string model made a number of predictions that were in direct conflict with observations)
     - (4) the *point-particle quantum field theory* of *quantum chromodynamics*

succeeded in describing the strong force [and] led to the dismissal of string theory - (relegated to the dustbin of science?).

c. 1974 John Schwartz and Joel Scherk, studying the puzzling messenger-like patterns of string vibration, realized that their properties matched perfectly those of the hypothesized messenger particle of the gravitational force - the *graviton*. p.138
    (1) They suggested that string theory had failed in its initial attempt because physicists had unduly constrained its scope
    (2) String theory is not just a theory of the strong force, it is a quantum theory that *includes gravity* as well.

d. 1984 Michael Green and John Schwartz established that the subtle quantum conflict afflicting string theory could be resolved [and that] string theory had sufficient breadth to encompass all of the four forces and all of matter as well
NOTE: vast areas of theoretical physics and abstract mathematics are required to understand string theory p.139

e. 1984-1986 *"the first superstring revolution"*
    (1) > 1000 research papers on string theory were written by physicists from around the world show[ing] conclusively that numerous features of the standard model *emerged naturally* and simply from the grand structure of string theory
    (2) String theory offers a far fuller and more satisfying explanation than is found in the standard model (the ultimate unified theory?).

f. Problems
    (1) In theoretical physics research, one is frequently confronted with the equations that are just too hard to understand or to analyze. p.140
    (2) The situation in string theory is even more difficult - even determining the equations themselves has proved to be so difficult that only approximate versions of them have so far been deduced (limited to finding approximate solutions to approximate equations).
    (3) physicists found that the approximations being used were inadequate to answer a number of essential questions hindering further developments

g. 1995 at The Strings Conference (held at USC), Edward Witten announced a plan for taking the next step igniting the *"second superstring revolution."*

3. The Greeks' Atoms, Again? p.141
    a. String theory claims that if the presumed point-particles of the standard model can be examined with a precision significantly beyond our present capacity, each would be seen to be made of a single, tiny, oscillating loop of string.
    LENGTH: about the Planck length (a hundred billion billion times [10^{20}] smaller than an atomic nucleus
    b. Of what are strings made?
        (1) possible answer number one: strings are fundamental *uncuttable constituents* - "atoms" in the truest sense of the ancient Greeks
            (a) having spatial extent
            (b) having composition without any content (the fundamental building block with no further substructure - not composed of any other substance) p.142
        (2) possible answer number two: strings are one more layer in the cosmic onion but not the final layer and are made up of yet smaller structures
        (3) possible answer number three: if string theory is incorrect, [and] not a

final theory of nature and truly off the mark, then, forget the strings and the irrelevant question of their composition

4. Unification through String Theory

a. The Standard Model

(1) takes the list of particles and their properties as experimentally measured *input.* p.143

(2) cannot be used to make any predictions without the input data of the fundamental particle properties.
NOTE: had experiments revealed a somewhat different particle content in the microscopic world, possibly interacting with somewhat different forces, these changes could have been fairly easily incorporated in the standard model by providing the theory with different input parameters.

(3) is too flexible [in structure] to be able to explain the properties of the elementary particles, as it could have accommodated a range of possibilities

b. String Theory

(1) is a unique and inflexible theoretical edifice

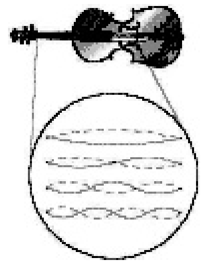
(2) requires no input beyond a single number (described below) that sets the benchmark scale for measurements.

(a) all properties of the microworld are within the realm of its explanatory power

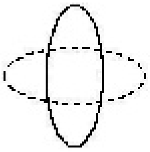
(b) the strings in string theory have a similar properties to the strings of a violin

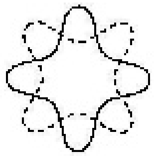
i) on a violin each string can undergo an infinite number of different vibrational patterns known as *resonances* (i.e. wave patterns whose peaks and troughs are evenly spaced and fit perfectly between the strings two fixed endpoints)

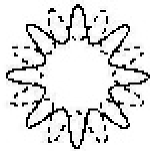
ii) *resonant vibrational patterns* are sensed by our ears as different musical notes



(c) the strings in string theory have resonant vibrational patterns - evenly spaced peaks and troughs fitting exactly along their spatial extent







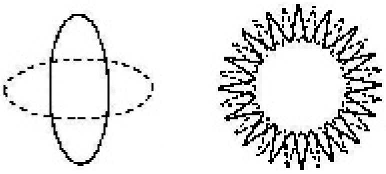
(3) CENTRAL FACT (of String Theory): *the different vibrational patterns of a fundamental string give rise to different masses and force changes.*

(a) the properties of an elementary particle (its mass and its various force charges) are determined by the precise resonant pattern of vibration that its internal string executes p.144

(b) the energy of a particular vibrational string pattern depends on its amplitude (the maximum displacement between peaks and troughs) and its wavelength (the separation between one peak and the next)

i) the greater the amplitude and the shorter the wavelength, the greater the energy

        - ii) more frantic vibrational patterns have more energy while less frantic ones have less energy p.145



        - iii) greater energy means greater mass and vice versa (per special relativity, energy and mass are two sides of the same coin)
      - (c) the mass of an elementary particle is determined by the *energy* of the vibrational pattern of its internal string
        - i) heavier particles have internal strings that vibrate more energetically
        - ii) lighter particles have internal strings that vibrate less energetically
      - (d) there is a direct association between the pattern of string vibration and a particle's response to the gravitational force since the mass of the particle determines its gravitational properties
      - (e) similar alignment exists between other detailed aspects of a string's pattern of vibration and its properties vis-à-vis other forces
      - (f) the observed properties of each elementary particle arise because its internal string undergoes a particular resonant vibrational pattern
    - (4) before the discovery of string theory the differences among the fundamental particles were explained by viewing each elementary particle as composed of different "stuff" p.146
    - (5) string theory declares that the "stuff" of all matter and all forces is the same - each elementary particle being composed of a single string with all strings absolutely identical
      - (a) differences between the particles arise because their respective strings undergo different resonant vibrational patterns
      - (b) the universe, composed of an enormous number of these vibrating strings, is akin to a cosmic symphony
    - (6) string theory provides the promise of a single, all-inclusive, unified description of the physical universe: a theory of everything (T.O.E.)

5. The Music of String Theory
  - a. What appear to be elementary particles are actually tiny pieces of vibrating string
  - b. The masses and the force charges of such elementary particles are the result of the way in which their respective strings are vibrating
  - c. If [one] can work out precisely the allowed resonant vibrational patterns of fundamental strings one should be able to *explain* the properties of the elementary particles [as] observed in nature. p.147
  - d. the possible resonant patterns of vibration [should] yield exactly the observed properties of the matter and force particles (string theory has the makings of a T.O.E. and is [possibly] capable of giving an explanation for why the particles

and forces have the properties they do)

- e. Strings come with a variety of tensions
- f. The one number that string theory requires in order to set its overall scale is the corresponding tension on its loops. p.148
- g. 1974 Joel Scherk and John Schwartz ...predict[ed]/calculated the tension on the strings of string theory
    - (1) the strength of the force transmitted by the proposed graviton pattern of string vibration is inversely proportional to the string's tension: a colossal tension of a thousand billion billion billion billion (10^{39}) tons (called *"Planck tension"*)
    - (2) fundamental strings are therefore extremely stiff

6. Three Consequences of Stiff Strings
    - a. 1st, (whereas the ends of a violin or piano string up and down ... no analogous constraining frame pins down the size of a fundamental string) huge string tension causes the loops of string theory to contract to a minuscule size (Planck length or 10^{-33})
    - b. 2nd, (because of the enormous tension), the typical energy of a vibrating loop in string theory is extremely high
        - (1) the greater the tension a string is under the harder it is to get to vibrate (i.e. two strings under different tension and vibrating in precisely the same way will not have the same energy - strings with higher tension will have more energy than strings with lower tension since more energy must be exerted to set it in motion p.149
        - (2) the energy of a vibrating string is determined by two things:
            - (a) the precise manner in which it vibrates
            - (b) the tension of the string
        - (3) the energy embodied in a string vibrational pattern is a whole number multiple of a minimal energy denomination
            - (a) this minimal energy denomination is proportional to the tension of the string (and is also proportional to the number of peaks and troughs in the particular vibrational pattern)
            - (b) the whole number multiple is determined by the amplitude of the vibrational pattern
        - (4) since the minimal energy denominations are proportional to the string's tension, and since this tension is enormous, the fundamental minimal energies are, on the usual scales of elementary particle physics, simply huge (multiples of the *Planck energy*)
        - (5) if *Planck energy* is translated into a mass using Einstein's formula $E=mc^2$ ... it corresponds to masses on the order of 10 billion billion times that of a proton (10^{19}) (this gargantuan mass is known as the *Planck mass*)
        - (6) the typical mass equivalent of a vibrating loop in string theory is generally some whole number (1,2,3 ...) times the *Planck mass*
        - (7) physicists often express this by saying that the "natural" or "typical" energy scale (and hence mass scale) of string theory is the *Planck scale*
        - (8) if the "natural" energy scale of string theory is some 10 billion billion times that of a proton, how can it possibly account for the far-lighter particles making up the world around us (e.g. electrons, quarks, photons ...)? p.150

BACKGROUND FOR THE ANSWER:

- (a) the uncertainty principle ensures that nothing is ever perfectly at rest
- (b) this [also] holds true for the loops in string theory (a string will always experience some amount of quantum vibration)
- (c) there can be energy *cancellations* between these quantum jitters and the more intuitive kind of string vibrations (see above)
  - i) energy associated with the quantum jitters of a string is *negative* and reduces the overall energy content of a vibrating string by an amount that is roughly equal to Planck energy
  - ii) the lowest energy vibrational string patterns ... are largely canceled ... yielding relatively low net energy vibrations
  - iii) these *lowest* energy vibrational patterns ... should provide contact between the theoretical description of strings and the experimentally accessible world of particle physics
- (d) ANSWER (from quantum mechanics): the comparatively light fundamental particles ... should arise ... from the fine mist above the roaring ocean of energetic strings

c. 3rd, strings can execute an infinite number of different vibrational patterns p.151

- (1) This means that there would have to be a corresponding never-ending sequence of elementary particles (i.e. each of the infinitely many resonant patterns of string vibration should correspond to an elementary particle)
- (2) The high string tension ensures that all but a few of these vibrational patterns correspond to extremely heavy (i.e. many times heavier than Planck mass) particles (the few being the lowest energy vibrations that have near-perfect cancellations with quantum string jitters)

7. Gravity and Quantum Mechanics in String Theory p.152

a. ... string theory [has] the ability to ameliorate the hostilities between the gravitational force and quantum mechanics

REVIEW: the problem in merging general relativity and quantum mechanics

- (1) central tenet of [general relativity]: space and time constitute a smoothly curving geometric structure
- (2) [central tenet/essential feature] of [quantum mechanics]: everything in the universe, including the fabric of space and time, undergoes quantum fluctuations that become increasingly turbulent when probed on smaller and smaller distance scales

b. String theory softens the violent quantum undulations by “smearing” out the short-distance properties of space.

8. The Rough Answer

a. One way [to] learn about the structure of an object is by hurling other things at it and observing the precise way in which they are deflected.

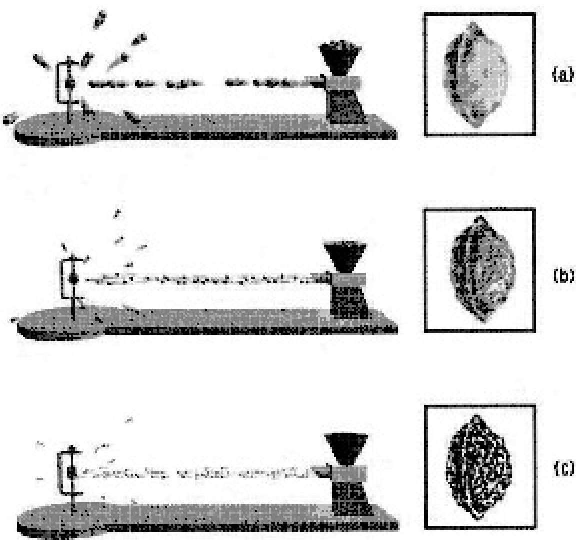
NOTE: particle accelerators are based on this principle p.153

b. As a general rule, the size of *the probe particle* use[d] sets a lower limit to the length scale ... [and] by observing the trajectories of what is deflected ... one is able to learn [something about an object]

c. Smaller probe particles are [fine enough and] tiny enough to enter and be deflected by the finest corrugations on an [object’s] surface

d. Useful probe particles can not be substantially larger than the physical features being examined; otherwise, they will be insensitive to the structures of interest.

NOTE: the illustration above shows the clarity of an object as determined by larger to smaller pellets (with diagram C showing great detail because of the smallness of particles directed against an object) p.154



e. On subatomic scales ... the most appropriate measure of a particle's probing sensitivity is its quantum wavelength ...

f. The distinction between point particles and strands of string becomes manifest (the string's inherent spatial extent prevents it from probing the structure of anything substantially smaller than its own size) p.155

g. 1988 David Gross and Paul Mende showed that continually increasing the energy of a string does *not* continually increase its ability to probe finer structures, in direct contrast with what happens for a point particle.

(1) when the energy of a string is increased beyond the value required for probing structures on the scale of the Planck length, the additional energy does not sharpen the string probe; rather, the energy causes the string to *grow* in size, thereby diminishing its short-distance sensitivity

(2) the extended nature of a string prevents [one] from using it to probe phenomena on sub-Planck-length distances.

h. *If the elementary constituent of the universe cannot probe the sub-Planck-scale distances, then neither it nor anything made from it can be affected by the supposedly disastrous short-distance quantum undulations.* p.156

(1) since the string has spatial extent, it also has limits on its short-distance sensitivity [and] cannot detect variations on sub-Planck-distance scales.

(2) the string smears out the jittery ultramicroscopic fluctuations of the gravitational field [and] this smearing smooths out [the resulting fluctuations] just enough to cure the incompatibility between general relativity and quantum mechanics.

(3) the infinities that arise in the point-particle approach to forming a quantum theory of gravity are done away with by string theory.

(4) in string theory there is no way to expose the sub-Planck-scale "imperfections" in the fabric of space (the notion that [one] can always dissect nature on ever smaller distances without limit is untrue).

9. A Slight of Hand? p.157

a. something has been solved:

(1) 1st, the preceding argument implies that the supposedly problematic sub-Planck-length spatial fluctuations are an artifact of formulating general relativity and quantum mechanics in a point-particle framework

(a) the central conflict of contemporary theoretical physics has been a problem of our own making

i) because all matter particles and all force particles were previously envisioned to be point-like objects with literally no spatial extent [one was] obligated to consider properties of the universe on arbitrarily short distance scales

ii) seemingly insurmountable problems were run into on the tiniest of distances

(b) string theory [indicates] that these problems were encountered only because the true rules of the game are not understood

i) there is a limit to how finely [one] can probe the universe

ii) there is a limit to how finely the conventional notion of distance can be applied to the ultramicroscopic structure of the cosmos

(c) the point-particle approach overstepped the bounds of physical reality

(d) the point-particle description was merely an idealization

(e) elementary particles do have some spatial extent

(2) 2nd, long ago some theoretical [physicians] suggest[ed] that nature's constituents might not actually be points but rather small undulating "blobs" or "nuggets"

NOTE: [but] it is very hard to construct a theory (whose fundamental constituent is not a point particle) that is consistent with the most basic of physical principles such as conservation of quantum-mechanical probability and the impossibility of faster-than-light-speed transmission of information. p.158

b. *string theory* respects all of the requisite properties inherent in any sensible physical theory and *is a quantum theory containing gravity*.

10. The More Precise Answer (describing more accurately how string theory calms the violent quantum jitters)

a. The extended nature of the string smears out the information that would be obtainable by point-particle probes, and ... does away with the ultra-short-distance behavior responsible for the central dilemma of contemporary physics.

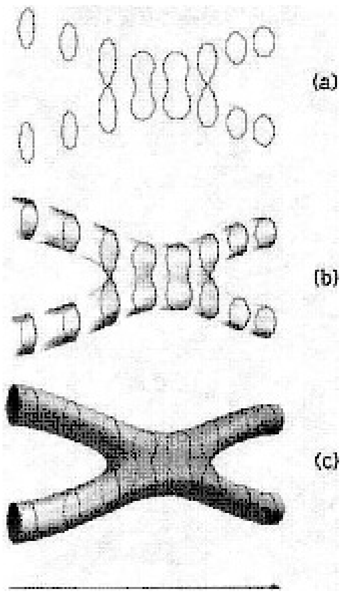
b. consider the way in which point particles would interact if they were actually to exist and, hence, how they could be used as physical probes:

(1) the most basic interaction is between two point particles moving on a collision course so that their trajectories will intersect

(2) point-particle interaction occurs at an identifiable point in space and time - a location [and time?] on which all observers can agree

(3) when elementary particles collide they scatter off one another and continue on deflected trajectories p.159

(4) this description changes if the objects thought to be zero-dimensional points turn out to be one-dimensional strings (i.e. the objects on a collision course are oscillating loops) p.160



NOTE: in the illustration to the right (a) two strings on a collision course can merge into a third string which subsequently can split apart into two strings traveling along deflected trajectories; (b) shows the same process as in (a) but emphasizing string motion; and (c) provides a "time-lapse photograph" of two interacting strings sweeping out a "world- sheet"

(5) string interaction occurs at an unidentifiable point in space and time - one on which all observers can not agree (the string, being an extended object, ensures that *there is no unambiguous location in space or moment in time when the strings first interact - rather, it depends upon the state of motion of the observer.* p.162

(6) the two incoming strings interact by merging together and producing a third string

c. If string theory is the ultimate description of the universe, there is no corrective lens to bring the supposed sub-Planck-scale fluctuations into sharp focus. p.164

d. The incompatibility of general relativity and quantum mechanics (which would become apparent only on sub-Planck-scale distances) is all avoided in a universe that has a lower limit on the distances that can be accessed, or even said to exist, in the conventional sense. p.165

11\. Beyond Strings?

a. Strings are special for two reasons:

(1) 1st, even though they are spatially extended they can be described consistently in the framework of quantum mechanics

(2) 2nd, among the resonant vibrational patterns there is one that has the exact properties of the graviton, thus ensuring that the gravitational force is an intrinsic part of its structure

b. String theory is *not* a theory that contains only strings, [rather], string theory actually includes ingredients with a variety of *different dimensions*

B. Chapter Seven: The "Super" in Superstrings p.166

1\. Introduction:

a. by following [a] precise notion of symmetry to its mathematical conclusion, physicists have found theories in which matter particles and messenger particles are far more closely intertwined than previously thought possible. p.167

b. Such theories, which unite not only the forces of nature but also the material constituents, have the greatest possible symmetry and for this reason have been called *supersymmetric*

c. Superstring theory is both the progenitor and the pinnacle example of a supersymmetric framework.

2\. The Nature of Physical Law

a. Physicists rely upon the stability of the universe (laws that are true today were true yesterday and will still be true tomorrow - fixed and unchanging) p.168

(1) Having never traveled to the opposite end of the universe, [one can not] definitely rule out the possibility that a whole new kind of physics prevails elsewhere, but everything points to the contrary.

(2) [but] imagine a universe in which the laws of physics are changing unpredictably from place to place and defiantly resisting any outside influence to conform

(3) imagine what things would be like if the laws of nature were varied (experiments carried out in one locale would have no bearing on the physical laws relevant somewhere else)

b. Physicists described these two properties of physical laws as *symmetries* of nature - i.e. nature treats every moment in time and every location in space identically (symmetrically) by ensuring that the same fundamental laws are in operation p.169

c. discussions of the special and general theories of relativity ... [reveal] ... other symmetries/symmetry principles of nature
    (1) the principle of relativity, which lies at the heart of special relativity, ... [argues] that all physical laws must be the same regardless of the constant-velocity relative motion that individual observers might experience (i.e. nature treats all such observers identically - symmetrically - [so] differences in observations reflect environmental details (the observers are a relative motion) even though their observations are governed by identical laws
        (a) through the equivalence principle of general relativity, Einstein significantly extended this symmetry by showing that the laws of physics are actually identical for all observers (even if they are undergoing complicated accelerated motion) p.170
        (b) once gravity is included in the framework, all possible observational vantage points are on a completely equal footing
    (2) *rotational symmetry* means that the laws of physics treat all possible orientations on an equal footing

3. Spin
    a. When any object spins, points on the axis of rotation itself - like the *central point* of a spinning Frisbee - do not move p.171
    b. [But] if something is truly point-like it has no other points that lie off of any purported spin axis (i.e. there is no notion of a point object spinning)
    c. [however, note this] quantum-mechanical surprise:
        (1) 1925 George Uhlenbeck and Samuel Goudsmit found that only one specific sort of electron motion could give rise to the magnetic properties suggested by data [having to do with properties of light emitted and absorbed by atoms]: *rotational* motion (i.e. spin)
        (2) they proclaimed that electrons both revolve *and* rotate
            (a) actually spinning? Yes and no ...
            (b) there is a quantum-mechanical notion of spin that is somewhat akin to the usual image but [is] inherently quantum mechanical in nature (having an experimentally verified quantum twist)
            (c) every electron in the universe, always and forever, *spins at one fixed and never changing rate*
            (d) the spin of electron is an *intrinsic* property (if it were not spinning it would not be an electron)
        (3) physicists have shown that these ideas about spin apply equally well to all of the matter particles that fill out three families [of particles] (cf. outline notes of page 9 from The Elegant Universe above) p.172
        NOTE: *all* of the matter particles (and their antimatter partners as well) have spin equal to that of the electron
        (4) physicists have shown that the non-gravitational force carriers (photons, weak gauge bosons, and gluons) also possess an intrinsic spinning characteristic that turns out to be *twice* that of the matter particles
        (5) regarding gravity, gravitons have twice the spin of photons, weak gauge bosons, and gluons

- d. In the context of string theory, spin is associated with the pattern of vibration that a string executes [but] it is misleading to think of the spin carried by a string as arising from it spinning literally around in space [nevertheless, this image gives a loose picture of what one ought to have in mind]
- e. ([below] Greene turns to the role *spin* plays in revealing the loophole in the Coleman-Mandala result concerning the possible symmetries of nature)

4. Supersymmetry and Superpartners
    - a. There is another kind of rotational motion that would not exist in a purely classical universe ([this] more subtle rotational motion associated with spin leads to another possible symmetry of the laws of nature p.173
    - b. When spin is considered, there is precisely *one more symmetry of the laws of nature* that is mathematically possible: *supersymmetry*
    - c. Supersymmetry ... can be associated with a ... change in observational vantage point in a "quantum-mechanical extension of space and time."
    - d. 1970s physicists realized that if the universe is supersymmetric, the particles of nature must come in *pairs* whose respective spins differ by half a unit - a pairing/partnering of matter and force particles called *superpartners*
    - e. But physicists found that *none* of the known particles (cf. outline notes of page 9 from <u>The Elegant Universe</u> above) could be superpartners of one another
    - f. ... if the universe incorporates supersymmetry, then every known particle must have an as-yet-undiscovered/undetected superpartner particle whose spin is half a unit less than its known counterpart
      HYPOTHETICALLY ...
        - (1) matter particles p.174
            - (a) electrons and *selectrons* (***s***upersymmetric-***electrons***)
            - (b) neutrinos and *sneutrinos* (***s***upersymmetric-***neutrinos***)
            - (c) quarks and *squarks* (***s***upersymmetric-***quarks***)
            - (d) etc.
        - (2) force particles
            - (a) photons and *photinos*
            - (b) gluons and *gluinos*
            - (c) W bosons and *winos*
            - (d) Z bosons and *zinos*
            - (e) etc.
    - g. Supersymmetry ... seems to ... require a whole slew of additional particles that wind up doubling the list of fundamental ingredients

5. The Case for Supersymmetry/*The Supersymmetric Standard Model*
    - a. 1st, physicists find it hard to believe that nature would respect almost but not quite all of the symmetries that are mathematically possible
    - b. 2nd, technical issues that are associated with quantum processes are solved if the theory is supersymmetric
        - (1) the basic problem
            - (a) every distinct particle species makes its own contribution to the microscopic quantum-mechanical frenzy
            - (b) certain processes involving particle interactions remain consistent only if numerical parameters in the standard model are fine-tuned to cancel out the most pernicious quantum effects
        - (2) [In] supersymmetry ... *bosons* ... and *fermions* ... tend to give canceling quantum-mechanical contributions p.175

- (a) like opposite ends of a seesaw, when the quantum jitters of a boson are positive, those of a fermion tend to be negative, and vice versa.
- (b) since supersymmetry ensures that bosons and fermions occur in pairs, substantial cancellations occur from the outset - significantly calm[ing] some of the frenzied quantum effects

- c. 3rd, [another] piece of circumstantial evidence for supersymmetry comes from the notion of *grand unification*
  - (1) one of the puzzling features of nature's four forces is the huge range in their intrinsic strengths
    - (a) the electromagnetic force has less than 1% of the strength of the strong force
    - (b) the weak force is some thousand times feebler than that
    - (c) the gravitational force is some hundred million billion billion billion (10^{-35}) times weaker still
  - (2) 1974 Sheldon Glashow and Howard Georgi proposed a "grand unification"of three of the four forces ... [taking] theoretical physics into an energy realm many orders of magnitude beyond that which anyone had previously dare to explore p.176
  - (3) 1974 Howard Georgi, Helen Quinn and Stephen Weinberg [expanded upon] the potential unity of the nongravitational forces within the grand unified framework
    - (a) regarding all electrically charged particles, quantum effects drive the strength of the electromagnetic force to get larger when examined on shorter distance scales p.177
      - i) a simple and well known feature of classical physics: the electrical attraction between two oppositely charged particles or the gravitational attraction between two massive bodies get stronger as the distance between the objects decreases p.176
      - ii) surpris[ingly], though ... quantum fluctuations(the seething mist of microscopic fluctuations) obscures the full strength of the electron's force field but as [one] get[s] closer to the electron [one] will have penetrated more of the cloaking particle-anti-particle mist and will be less subject to [the mist's] diminishing influence - impl[ying] that the strength of the electron's electric field will *increase* as [one] get[s] closer to it
      - iii) the *intrinsic* strength of the electromagnetic force increases on shorter distance scales not merely because [one is] closer to the electron but also because more of the electron's intrinsic electric field becomes visible
    - (b) regarding the other forces and how their intrinsic strengths vary with distance p.177
      - i) 1973 David Gross, Frank Wilczek and David Politzer [noted that] the quantum cloud of particle eruptions and violations *amplifies* the strengths of the strong and weak forces - imply[ing] that, examined on shorter distances, more of this seething cloud is penetrated, [and there is]

less amplification so the strengths of these forces get *weaker* when they are probed on shorter distances

ii) Howard Georgi, Helen Quinn and Stephen Weinberg showed that when these effects of the quantum frenzy are carefully accounted for the net result is that the strengths of all three nongravitational forces are driven together ... [and] whereas the strengths of these forces are very different on scales accessible to current technology this difference is actually due to the different effect that the haze of microscopic quantum activity has on each force ([actually] the three nongravitational forces strengths appear to become equal)

(4) since 1974 experimentalists have refined the measured strengths of the three nongravitational forces under everyday conditions p.178

(a) 1st, the strengths of the three nongravitational forces *almost agree but not quite* at tiny distance scales

(b) 2nd, this tiny but undeniable discrepancy in their strengths *vanishes* if supersymmetry is incorporated [b/c] the new superpartner particles required by supersymmetry contribute additional quantum fluctuations and these fluctuations are just right to nudge the strengths of the forces to converge with one another

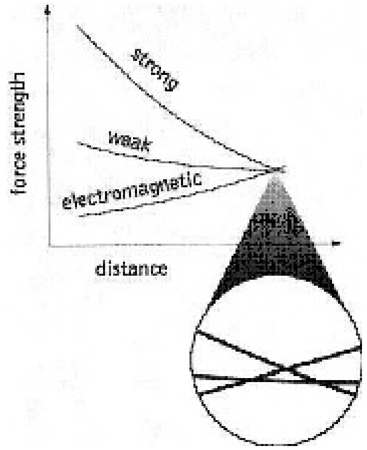
(5) to many physicists, it is difficult to believe that nature would choose the forces so that they almost, but not quite, have strengths that microscopically unify/become equal

(6) supersymmetry deftly refines its shape so that all pieces firmly lock into place

d. reasons for believing in, or at least not rejecting, supersymmetry are far from airtight p.179

(1) [while] supersymmetry modifies the intrinsic strengths of the three nongravitational forces at tiny distances in just the right way for them to merge together into a grand unified force, nothing in the design of nature dictates that these force strengths must exactly match on microscopic scales p.180

(2) [and] a simpler explanation for why the superpartner particles have never been found is that our universe is not supersymmetric and, therefore, the superpartners do not exist



e. But the case for supersymmetry is strengthened ... when consider[ing] its role in string theory

6. Supersymmetry in String Theory

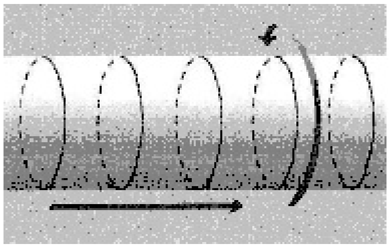
a. The first theory based on the string concept was called the *bosonic string theory* ("*bosonic"* b/c all of the vibrational patterns of the bosonic string have spins that are a whole number - there are no fermionic patterns, i.e. no patterns with spins differing from a whole number by a half unit)

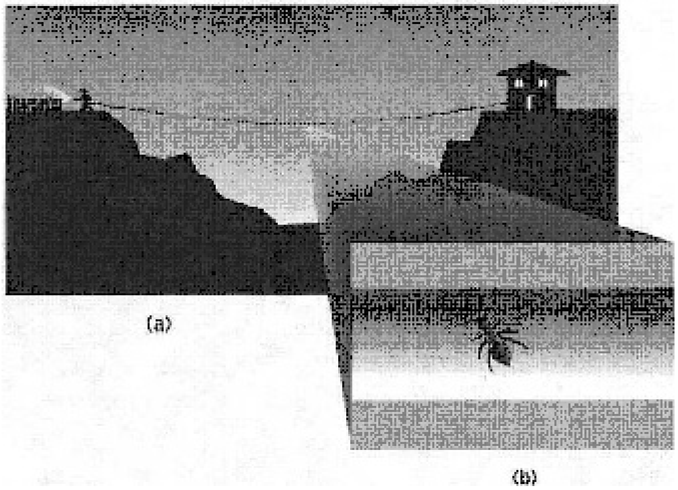
(1) two problems

        - (a) 1st, if string theory was to describe all forces and all matter, it would somehow have to incorporate fermionic vibrational patterns
        - (b) 2nd, there was one pattern of vibration (*"tachyon"*) in bosonic string theory whose mass (actually mass squared) was negative
      - (2) [thus] the bosonic string theory was missing something essential p.181
    - b. 1971 Pierre Ramond sought to modify the bosonic string theory to include fermionic patterns of vibration
    - c. Through [Ramond's] work and subsequent results of John Schwartz and Andre Neveu a new version of string theory emerged - the bosonic and the fermionic patterns of vibration appeared to come in pairs (for each bosonic pattern there was a fermionic pattern and vice versa)
    - d. 1977 Ferdinando Gliozzi, Joel Scherk and David Olive [incorporated] supersymmetry [with] the observed pairing of bosonic and fermionic vibrational patterns)
      - (1) supersymmetric string theory/superstring theory was born
      - (2) the troublesome tachyon vibration of the bosonic string does not afflict the superstring
    - e. Julius Wess and Bruno Zumino realized that supersymmetry (the new symmetry emerging from the reformulation of string theory) was applicable even to theories based on point particles
      - (1) ... [this] launched a tremendous amount of subsequent research on ... *supersymmetric quantum field theory*
      - (2) this point-particle theory owes a great debt to string theory
    - f. String theory is the only [known] way ... to merge general relativity and quantum mechanics. p.182
    - g. ... only the supersymmetric version of string theory ... avoids the pernicious tachyon problem and has fermionic vibrational patterns that can account for the matter particles constituting the world around us.
    - h. Supersymmetry ... [fits] ... with string theory's proposal for a quantum theory of gravity, as well as its grand claim of uniting all forces and all of matter.
  - 7. A Super-Embarrassment of Riches
    - a. By 1985 ... physicists realized that supersymmetry ... could ... be incorporated into string theory in ... *five* different ways:
      - (1) *Type I theory*
      - (2) *Type IIA theory*
      - (3) *Type IIB theory*
      - (4) *Heterotic type O(32) theory* (pronounced "oh-thirty-two")
      - (5) *Heterotic type* E_8 *X* E_8 *theory (*pronounced "e-eight times e-eight) p.183
    - b. ... five different versions of what is supposedly the T.O.E. ...was an embarrassment for string theorists ... [who] dream ... that the search for the ultimate answer will lead to a single, unique, absolutely, inevitable conclusion.
    - c. ... recent research show[s] that ... the five different theories are ... actually five different ways of describing one *and the same overarching* theory.
- C. Chapter Three: More Dimensions than Meet the Eye p.184
  - 1. Introduction: string theory requires that conceptions of space and time be subjected to yet another radical revision (even the generally accepted number of dimensions of our universe ... is dramatically and convincingly overthrown)
  - 2. The Illusion of the Familiar

a. ... we ... identify ... three independent spatial dimensions ... the “left-right dimension,” the “ back-forth dimension,” and the “up-down dimension.” p.185
b. ... any location in the universe can be fully specified by giving three pieces of data: where it is relative to these three spatial dimensions.
c. ... Einstein’s work encourages us to think about time as another dimension (the “future-past dimension”).
d. [One specifies] events in the universe by telling where and when they occur.
e. 1919 Polish mathematician Theodor Kaluza ... suggested that the universe might *not* actually have three spatial dimensions; it might have *more*.
f. Kaluza’s suggestion has revolutionized our formation of physical law.

3. Kaluza’s Idea and Klein’s Refinement p.186
   a. The suggestion that our universe might have more than three spatial dimensions ... is concrete and thoroughly plausible.
   b. ... spatial dimensions ... come in two varieties p.187
      (1) large, extended and ... directly manifest (e.g. an ant walking the length of garden hose)
      (2) or ... small, curled up and much more difficult to detect (e.g. an ant walking around the circumference of a garden hose)

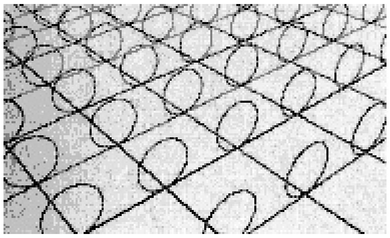




   c. 1919 Kaluza ... proposed that the spatial fabric of the universe might possess more than the three dimensions of common experience (weaving together Einstein’s general relativity and Maxwell’s electromagnetic theory into a single, unified conceptual framework).
   d. ... Kaluza’s work ... subsequently ... refined (1916) by Swedish mathematician Oskar Klein ... is that *the spatial fabric of our universe may have both extended and curled-up dimensions.* p.188
      (1) ... dimensions that are large, extended and easily visible (the three dimensions of common experience)
      (2) ... also ... additional spatial dimensions that are tightly curled up into a tiny space ...
   e. Theodore Kaluza and Oscar Klein proposed that our spatial universe ... has three large, extended spatial dimensions and one small, circular dimension - for a total of four spatial dimensions.
      (1) ... as [one] ... journey[s] toward the most microscopic examination of space ... a new, curled-up, circular dimension becomes apparent. p.190
      (2) they suggested that the extra circular dimension exists at *every* point in

the extended dimensions, just as a circular girth of the garden hose exists in every point along its ... horizontal extent.

f. ... the circular dimension is a new dimension, one that exists at every point in the familiar extended dimensions just as each of the up-down, left-and right, and back-fourth dimensions exist at every point as well. p.191



g. ILLUSTRATION: the grid lines represent extended dimensions of common experience, whereas the circles are a new, tiny, curled-up dimension.

h. To specify ... [a] spatial location ... [one] would need to [specify five pieces of space-time information]: where it is in the three familiar extended dimensions, ... where it is in the circular dimension, [and where it is in time if time is added in].

i. The universe may very well have more dimensions than meet the eye.

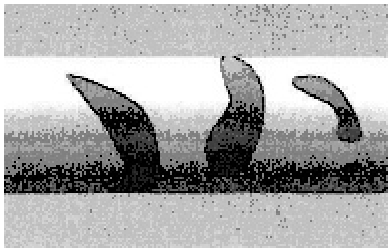
j. ... physicists have called the possibility of extra tiny space dimensions *Kaluza-Klein theory.* p.192

4. Comings and Goings on a Garden Hose

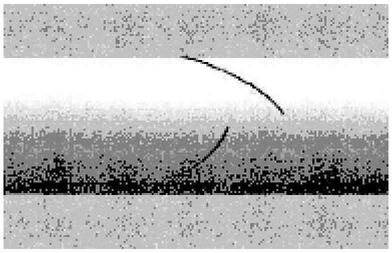
a. Physicists ... hone their intuition about ... extra dimensions by contemplating what life would be like if ... [one] lived in an imaginary *lower*-dimensional universe (cf. Edwin Abbott's 1884 classic popularization *Flatland*)

b. Imagine a two-dimensional universe shaped like [a] garden hose ... [wherein] the surface ... is *all there is* as far as spatial extent (with two-dimensional beings). ("a" below) ...or think of [living in just one dimension] ("b" below) (with beings having no thickness at all) p.193

(a)



(b)



c. The [mental] evolution from one to two observably large space dimensions [would be] dramatic [but] ... why stop there? (why not 3rd, 4th or more ... dimensions) p.195

5. Unification in Higher Dimensions p.196

a. ... Einstein had formulated general relativity in the familiar setting of the universe with three spatial dimensions and one time dimension [but] the mathematical formalism of his theory ... could be extended ... to ... analogous equations for a universe with additional space dimensions.

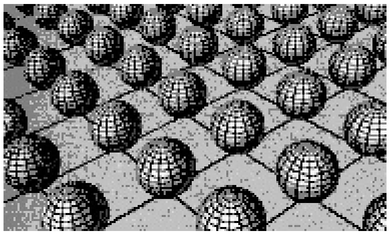
b. Under the "modest" assumption of one extra space dimension, Kaluza carried out the mathematical analysis and explicitly derived new equations beyond those Einstein originally derived - extra equations associated with the new dimension.

c. Kaluza realized that ... the extra equations were none other than those Maxwell had written down in the 1880s for describing the electromagnetic force.

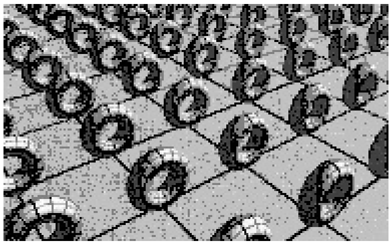
d. By adding another space dimension, Kaluza had united Einstein's theory of

gravity with Maxwell's theory of light. p.197
   (1) [prior to this] gravity and electromagnetism were thought of as two unrelated forces
   (2) [Kaluza's] theory argued that both gravity and electromagnetism are associated with ripples in the fabric of space (gravity carried by ripples in the familiar three space dimensions and electromagnetism carried by ripples involving the new, curled-up dimension)
e. Subsequent detailed study of Kaluza's proposal showed that it was in serious conflict with experiential data (thus many physicists lost interest but Einstein and others continued to dabble with the possibility of extra curled-up dimensions).
f. the grandest question of all [remained]: the ... conflict between general relativity and quantum mechanics p.198
g. ... success in formulating a quantum theory of three of nature's forces emboldened physicists to try to bring the fourth, gravity, into the fold
h. ... .[becoming] more open to comparatively radical approaches ... [the] Kaluza-Klein theory was resuscitated.

6. Modern Kaluza-Klein Theory
   a. [with] quantum mechanics fully formulated and experimentally verified, [with] the strong and weak forces discovered and largely understood, some physicists suggested that Kaluza's original proposal had failed because he was unaware of these other forces and had therefore been too *conservative* in his revamping of space. p.199



   b. More forces meant the need for even more dimensions [and] ... a single new, circular dimension ... was just not enough.
   c. 1970s ... research ... was underway focusing on higher-dimensional theories with numerous curled-up spatial directions (like the two extra dimensions that are curled up into the surface of balls (or spheres).
   d. Beyond proposing a different number of extra dimensions, one can also imagine other shapes for the extra dimensions (e.g. the two extra dimensions curled up in the shape of hollow doughnuts). p.200
   e. ... more complicated possibilities can be imagined in which there are ... essentially any number of extra spatial dimensions, curled up into a wide spectrum of exotic shapes.



   f. The most promising of the higher dimensional proposals were those that also incorporated supersymmetry.
      (1) The name *"higher-dimensional super gravity"* was coined to describe those theories encompassing gravity, extra dimensions and supersymmetry.
      (2) Physicists hoped that the partial canceling of the most severe quantum fluctuations, arising from the pairing of superpartner particles, would help to soften the hostilities between gravity and quantum mechanics.
         (a) various versions of higher-dimensional supergravity looked quite promising at first ... but the old conundrums persisted.
         (b) ... pernicious short-distance quantum undulations were lessened by supersymmetry, but not sufficiently to yield a sensible theory.

    - (c) ... a single, sensible, higher-dimensional theory incorporating all features of forces and matter was difficult to find. p.201
  - g. In 1984 string theory took center stage [providing] a quantum-mechanically consistent manner [by which] to tie together ... a unified theory.
- 7. More Dimensions and String Theory
  - a. ... our universe *may* have additional curled-up spatial dimensions
  - b. ... the act of postulating ... experimentally untested ... possibilities might seem ... arbitrary (and such was the case until string theory).
  - c. string theory resolves the central dilemma confronting contemporary physics: the incompatibility between quantum mechanics and general relativity
  - d. [string theory] unifies ... understanding of all nature’s fundamental material constituents and forces.
  - e. to accomplish [c and d above] ... string theory *requires* that the universe have extra space dimensions
    REASON(S):
    - (1) quantum mechanics [shows] that predictive power is fundamentally limited to asserting that such-and-such [an] outcome will occur with such-and-such probability
    - (2) ... quantum-mechanical theory has gone haywire [if] ... particular calculations yield “probabilities” that are *not* within an acceptable range
      - (a) e.g. the ... incompatibility between general relativity and quantum mechanics in a point-particle framework is: calculations result in infinite probabilities p.202
      - (b) ... string theory cures these infinities. But ... a residual, somewhat more subtle problem still remains: in the early days of string theory ... certain calculations yielded negative probabilities (which are also outside of the acceptable range)
    - (3) ... physicists ... found the cause of this unacceptable feature
      - (a) if a string is constrained to ... a two-dimensional [universe] ... the number of independent directions in which it can vibrate is reduced to *two*: the left-right and back-forth dimensions ...
      - (b) ... however ... in a universe with three spatial dimensions, a string can vibrate in three independent directions ... (since the string can also oscillate in the up-down direction)
      - (c) in a universe with ever more spatial dimensions, there are ever more independent directions in which [a string] can vibrate
    - (4) ... physicists found that the troublesome calculations were highly sensitive to the number of independent directions in which a string can vibrate
    - (5) the negative probabilities arose from a *mismatch* between what the theory required and what reality seem to impose:
      - (a) calculations showed that if strings can vibrate in nine independent spatial directions, all of the negative probabilities with cancel out
      - (b) [but what if] if string theory ... describe[s] our world with [only] three spatial dimensions?
      - (c) Kaluza and Klein provided a loophole: p.203
        - i) strings are so small, [that] not only can they vibrate in large, extended dimensions, strings can also vibrate in [dimensions] that are tiny and curled up

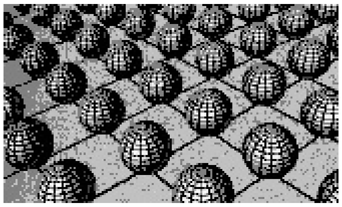
        ii) [thus] the nine-space-dimension requirement of string theory can be met in *our* universe by assuming ... that in addition to our familiar three extended spatial dimensions there are six other curled-up spatial dimensions
        iii) in this manner string theory is saved from elimination
    (6) string theory *requires* postulating the existence of extra dimensions - nine space dimensions and one time dimension for a total of 10 dimensions

8. Some Questions
    a. 1st, why does string theory require nine space dimensions to avoid nonsensical probability values?
        (1) The calculation underlying the conclusion ... turns out to be *approximate*
        (2) Mid-1990s Edward Witten ... gave convincing evidence that the approximate calculation actually misses one space dimension p.204
        (3) [Witten] ... argued ... [that string theory] actually requires ten space dimensions and one time dimension, for a total of 11 dimensions. (see Chapter 12 below)
    b. 2nd, why [are the] three space and one time dimensions large and extended while all of the others are tiny and curled up?(if the [approximate] equations of string theory show that the universe [indeed must have] nine space dimensions and one time dimension)
        (1) why not all large and extended or all tiny and curled up?
        (2) why not other possibilities in between?
        (3) currently no one knows the answer to this question!
        NOTE: in what follows below [it] will [be] assume[d] that all but three space dimensions are curled up, in accordance with what is seen around us
    c. 3rd, is it possible that some [of the] additional [dimensions] are *time* dimensions as opposed to additional space dimensions?
        (1) what would it mean to have multiple times?
        (2) what about a curled-up time dimension?
            (a) if [one were to] walk around an extra space dimension that is curled up like a circle, [one] would find [one's self] returning to the same position over and over again as [one] traverses complete circuits p.205
            (b) one is able to return to the same location in space as often as one likes - if a curled-up dimension is a time dimension, traversing it means returning, after a temporal lapse, to *a prior instant in time*
            (c) time, as [currently] known ... is a dimension [one] can traverse in only one direction with absolute inevitability - never able to return to an instant after it has passed
        (3) Greene will stick to the more "conventional" approach in which all of the curled-up dimensions are space dimensions.
9. The Physical Implications of Extra Dimensions
    a. extra dimensions would have important *indirect* effects on observed physics
    b. in string theory, this connection between the microscopic properties of space and

the physics [one] observe[s] is particularly transparent.

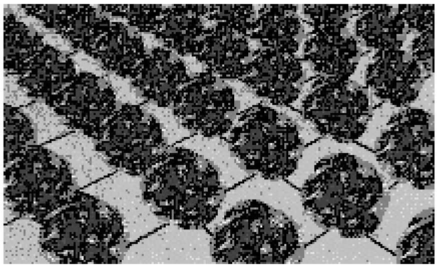
- (1) ... masses and charges of particles in string theory are determined by the possible resonant vibrational string patterns
- (2) ... resonance patterns are influenced by spatial surroundings.
- (3) ... a string is equally free to oscillate in any of the extended directions at any moment p.206
- (4) curled-up spatial dimensions [would] have [an] impact on the possible vibrational patterns of a string.
- (5) since tiny strings vibrate through all of the spatial dimensions, the precise way in which the extra dimensions are twisted up and curled back on each other strongly influences and tightly constrains the possible resonant vibrational patterns
- (6) *extra dimensional geometry determines fundamental physical attributes like particle masses and charges that we observe in the usual three large space dimensions of common experience.*
- (7) a tiny string can probe a tiny space ... oscillating as it travels(the geometrical form of the extra dimensions plays a critical role in determining resonant patterns of vibration)
- (8) one of the most far-reaching insights of string theory [is that] ... fundamental properties of the universe are determined, in large measure, by the geometrical size and shape of the extra dimensions.

10. What Do the Curled-Up Dimensions Look Like? p.207
    - a. ... string theory equations severely restrict the geometrical form extra spatial dimensions can take.
    - b. 1984 Philip Candelas, Gary Horowitz, Andrew Strominger and Edward Witten showed that a particular class of six-dimensional geometrical shapes, known as *Calabi-Yau spaces* or *Calabi-Yau shapes* can meet the (above) conditions.
        - (1) named in honor of two mathematicians: Eugenio Calabi and Shing-Tung Yau whose research plays a central role in understanding these spaces



        - (2) a [limited] example of Calabi-Yau space is given in the 1st illustration (above) - limited b/c of the attempt to represent a six-dimensional shape on a two-dimensional piece of paper)

          NOTE: imagine replacing the figures of the example given to the right with the 2nd example given [below]



        - (3) ... at every point in the three familiar extended dimensions, string theory claims that there are six hitherto unanticipated dimensions, tightly curled up into one of these rather complicated-looking shapes
        - (4) these dimensions are an integral and ubiquitous part of the spatial fabric - [and] they exist everywhere
    - c. What are the physical properties that emerge from strings that vibrate through them? (see next chapter below) p.209

D. Chapter Nine: The Smoking Gun: Experimental Signatures p.210

1. Introduction: although string theory has the potential to be the most predictive theory

that physicists have ever studied, physicists have not as yet been able to make predictions with a precision necessary to confront experimental data. p.211

2. Crossfire p.213
    a. traditionalists want theoretical work to be tied to experimental observation
    b. others think [it is appropriate] to tackle questions that are beyond ... present technological ability to directly test
3. The Road to Experiment p.215
    a. without monumental technological breakthroughs [it will never be possible to] focus on the tiny length scales necessary to see a string directly.
    b. ... today's technology would [require] an accelerator the size of the *galaxy* to see individual strings (Shmuel Nussinov's study indicates that an accelerator the size of the whole *universe* would be required)
    c. ... test[ing] string theory experimentally ... will have to be in an indirect manner.
        (1) Philip Candelas, Gary Horowitz, Andrew Strominger and Edward Witten took the first steps toward this goal
        (2) they found that the extra dimensions in string theory must be curled up into a Calabi-Yau shape and worked out some of the implications this has on the possible patterns of string vibrations. p.216
    d. REVIEW: [there are] three families of elementary particles with the particles in each successive family becoming increasingly massive (cf. outline notes above from page 9 in <u>The Elegant Universe</u>)
    e. QUESTION: Why families and why three?
        (1) a typical Calabi-Yau shape contains *holes* that are analogous to those found at the center of a phonograph record ... doughnut ... or "multidoughnut"
        (2) in the higher dimensional Calabi-Yau context ... a variety of different types of holes ... can arise (holes which themselves can have a variety of dimensions: "multidimensional holes")
        (3) there is a *family* of lowest-energy string vibrations associated with each *hole* in the Calabi-Yau portion of space.
        (4) ... existence of multiple holes ... means that the patterns of string vibrations will fall into multiple families
    f. string theory proclaims that the family organization observed experimentally, rather than being some unexplainable feature of either random or divine origin, is a reflection of the number of holes in the geometrical shape comprising the extra dimensions! p.217
        (1) ... the number of holes contained in each of the tens of thousands of known Calabi-Yau shapes spans a wide range (3, 4, 5, 25 ... 480 holes)
        (2) *the problem is that at present no one knows how to deduce from the equations of string theory which of the Calabi-Yau shapes constitutes the extra spatial dimensions.*
        (3) ... finding the principle for choosing among Calabi-Yau shapes is a problem ... unresolved.
    g. The number of families is but one experimental consequence of the geometrical form of the extra dimensions.
        (1) ... other consequences of the extra dimensions include the detailed properties of the force and matter particles (e.g. the masses of the particles in each family depend upon the way in which the boundaries of the various multidimensional holes in the Calabi-Yau shape intersect and

overlap with one another).

(2) ... as strings vibrate through the extra curled-up dimensions, the precise arrangement of the various holes and the way in which the Calabi-Yau shape folds around them has a direct impact on the possible resonant patterns of vibration.

h. ... as with the number of families, string theory can provide us with a framework for answering questions ... on which previous theories are ... silent. p.218
NOTE: ... [but] such calculations require ... knowing] which Calabi-Yau space to take for the extra dimensions.

i. ... string theory provides a framework for explaining the observed messenger-particle content of our universe, [i.e.] for explaining the properties of the fundamental forces ... (if [it was known into] which Calabi-Yau Shape the extra dimensions are curled

j. why [can it not be figured out] which is the “right” Calabi-Yau shape?

(1) ... the inadequacy of the theoretical tools currently being used to analyze string theory

(2) ... the mathematical framework of string theory is so complicated that ... only approximate calculations have been able to be performed through a formalism known as *perturbation theory.*

k. ... with ... the [in]ability to select one Calabi-Yau space from the many, no definite experimentally testable conclusions can be drawn.

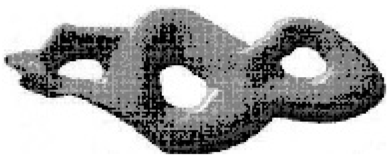
4. Exhausting Possibilities p.219

a. ... [al]though [one can not] as yet figure out which Calabi-Yau shape string theory selects, does any choice yield physical properties that agree with what [is] observe[d] ... (i.e. that match[es] reality)?

b. A sensible start is to focus only on those Calabi-Yau shapes that yield three families.

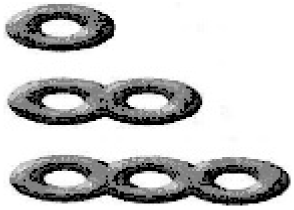
(1) ... start with a three-holed Calabi-Yau space and smoothly deform its shape without changing the number of holes ...

(2) e.g. the shape of a multi-handled doughnut could be deformed in many ways ... without changing the number of holes it contains (an infinite sequence of shapes)



c. problem:

(1) the detailed physical properties of string vibrations, their masses and their response to forces, are very much affected by such detailed changes in shape, but ... [what should be the] means of selecting one possibility over any other?
p.220



(2) it is not possible to figure out the physics corresponding to an infinite list of different shapes.

(3) the approximate equations ... currently use[d] are not powerful enough to work out the resulting physics fully for any given choice of Calabi-Yau shape.

  - d. ... [a few entries] in the Calabi-Yau catalog give rise to a world that is in ... rough agreement with ... what is actually observed p.221
  - e. ... there *are* examples of Calabi-Yau spaces that, when chosen for the curled-up dimensions required by string theory, give rise to string vibrations that are closely akin to the particles of the standard model.
  - f. ... string theory successfully stitches the gravitational force into this quantum-mechanical framework.
  - g. There are ... string theoretic *pre*dictions that experimental physicists can attempt to confirm.

5. Superparticles
  - a. ... current theoretical hurdles ... force [the] search for *generic*, rather than specific, aspects of a universe consisting of strings.
    - (1) generic: characteristics that are so fundamental to string theory that they are fairly insensitive to, if not completely independent of, those detailed properties of the theory that are now beyond ... theoretical purview.
    - (2) one generic characteristic/feature [of string theory is] supersymmetry - that super partners *exist*
      - (a) ... a fundamental property of string theory is that it is highly symmetric, incorporating not only intuitive symmetry principles but respecting, as well, the maximal mathematical extension of these principles, supersymmetry. p.222
      - (b) ... patterns of string vibrations come in superpartner pairs differing from each other by a half unit of spin.
      - (c) If string theory is right, then some of the string vibrations will correspond to the known elementary particles.
      - (d) due to the supersymmetric pairing ... string theory makes the *prediction* that each such known particle will have a superpartner
    - (3) no superpartners of the known elementary principles have ever been observed
      - (a) [explanation #1]: string theory is wrong and they do not exist
      - (b) [explanation #2]: superpartners are very heavy and beyond current capacity to observe the experimentally
  - b. if superpartner particles are found this fact alone will not establish that string theory is correct [b/c] supersymmetry has also been successfully incorporated into point-particle theories
  - c. but if superpartner particles are not found this fact alone will not rule out string theory

6. Fractionally Charged Particles p.223
  - a. Electric charge is another experimental signature of string theory.
  - b. In string theory ... it is possible for there to be resonant vibrational patterns corresponding to particles of significantly different electric charges.
  - c. These unusual charges can arise if the curled-up dimensions have a certain geometrical property: holes with the peculiar property that strings encircling them can disentangle themselves only by wrapping around a specified number of times.
  - d. ... the number of windings required to get disentangled manifests itself in the allowed patterns of vibration by determining the denominator of the fractional charges.
  - e. ... there is no compelling reason for such exotic electric-charge fractions to exist

in *any* point-particle theory

f. Their possible emergence from simple geometrical properties that the extra dimensions can have makes these unusual electric charges a natural experimental signature for string theory.

g. No such exotically charged particles have ever been observed ... (if they do exist, their masses must be beyond present technological means) p.224

7. Some Longer Shots (other ways in which evidence for string theory might be found)
   a. Astronomical
      (1) Astronomers might one day see a direct signature of string theory in the data they collect from observing the heavens. (Edward Witten)
      NOTE: The energy of the Big Bang ... would have been high enough to produce a few macroscopically large strings that, through cosmic expansion, might have grown to astronomical scales.
      (2) " ... nothing would settle the issue quite as dramatically as seeing a string in a telescope." (Edward Witten)
   b. Five examples of other possible experimental signatures of string theory:
      (1) 1st, a compelling explanation of present and future neutrino data, especially if experiments ultimately show that neutrinos do have a tiny but nonzero mass. (are neutrinos just very light or massless?)
      NOTE: according to the standard model neutrinos are massless
      (2) 2nd, certain hypothetical processes that are forbidden by the standard model/conventional theory but may be allowed by string theory
      NOTE: if observed, any one of these processes would provide fertile ground for string theory to offer an explanation p.225
      (3) 3rd, [since there are] particular patterns of string vibration for certain Calabi-Yau shapes that can ... contribute new, tiny, long-range force-fields, ... discovery of the effects of any such new forces could reflect some of the new physics of string theory
      (4) 4th, through its many possible patterns of resident vibration, string theory suggests a number of candidates for identifying what astronomers describe as "*dark matter*"
      (5) 5th, physicists have realized that there is no explanation for *why* the cosmological constant (which Einstein temporarily imposed on his original equations of general relativity to ensure a static universe) should be zero
         (a) the cosmological constant can be interpreted as a kind of overall energy stored in the vacuum of space, and hence its value should be theoretically calculable and experimentally measurable
         (b) [currently] ... [observational] measurements and calculations lead to a colossal mismatch
            i) observations show that the cosmological constant is either zero ... or [is] quite small
            ii) calculations indicate that quantum-mechanical fluctuations in the vacuum of empty space tend to *generate* a nonzero cosmological constant whose value is some 120 orders of magnitude larger than the experiment allows
         (c) can calculations in string theory improve on this mismatch and explain why the cosmological constant is zero, or if experiments do ultimately establish that its value is small but nonzero, can

string theory provide an explanation (such would provide the compelling piece of evidence in support of string theory)

8. An Appraisal p.226

a. ... string theory has been hailed as the most important and exciting development in theoretical physics since the discovery of quantum mechanics.

b. [but] the substantial number of physicists ... pursuing string theory ... are taking a risk: that a lifetime of effort might result in an inconclusive outcome

c. ... string theory uncover[s] remarkably new physical characteristics of a string-based universe - characteristics that reveal a subtle and deep coherence in the workings of nature (generic features that ... will be basic properties of a universe built of strings) p.227

V. Part IV: String Theory and the Fabric of Spacetime p.229

A. Chapter 10: Quantum Geometry p.231

1. Introduction

a. Einstein ... overthrew the centuries-old Newtonian framework and gave ... a radically new and demonstrably deeper understanding of gravity.

b. Favorable historical circumstances ... contributed to Einstein success.

(1) the 19th-century mathematical insights of Georg Bernhard Riemann ... established the geometrical apparatus for describing curved spaces of arbitrary dimension ... break[ing] the chains of flat-space Euclidean thought and pav[ing] the way for a democratic mathematical treatment of geometry on all varieties of curved surfaces.

(a) Riemann's insights provide the mathematics for quantitatively analyzing warped spaces

(b) Einstein ... recogniz[ed] that this body of mathematics was tailor-made for implementing his new view of the gravitational force ... align[ing] perfectly with the physics of gravity.

(2) ... string theory [provides] ... a quantum-mechanical description of gravity that ... modifies general relativity when the distances involved become as short as the Planck length. p.232

(3) Riemannian geometry, the mathematical core of general relativity)must be modified to reflect the short-distance physics of string theory.

(a) general relativity asserts that the curved properties of the universe are described by Riemannian geometry

(b) string theory asserts that this is true only if ... the fabric of the universe [is examined] on large enough scales

(4) this new geometrical framework/new kind of geometry is called *quantum geometry* (which must emerge [from] scales as small as the *Planck length* and align with the new physics of string theory

2. The Heart of Riemannian Geometry

a. Opening illustration:

(1) if [one] jump[s] on a trampoline, the weight of [one's] body causes it to warp by stretching its elastic fibers - most severe[ly] under [one's] body and ... less noticeab[ly] toward the trampoline's edge.

(2) this example cuts to the heart of Riemann's mathematical framework for describing warped spaces

- b. Riemann ... showed that a careful analysis of the distances between all locations on or in an object provides a means of quantifying the extent of its curvature.
  - (1) the greater the (nonuniform) stretching (i.e. the greater the deviation from the distance relations on a flat shape) the greater the curvature of the object.
  - (2) e.g. a trampoline is most significantly stretched right under one's body and ... the distance relations between points in this area are most severely distorted
- c. Einstein adopted Riemann's mathematical discoveries - by giving them a precise physical interpretation - that the curvature of space time embodies the gravitational force
- d. mathematically, the curvature of space time (like the curvature of the trampoline) reflects the distorted distance relations between its *points*.
  - (1) The gravitational force felt by an object is a direct reflection of this distortion
  - (2) By making [an] object smaller and smaller, the physics and mathematics align ever more precisely as [one] get[s] closer and closer to physically realizing the abstract mathematical concept of a *point*.
- e. But string theory limits how precisely Riemann's geometrical formalism can be realized by the physics of gravity, because there is a limit to how small [one] can make any object.
  - (1) at the string level it is impossible to get any smaller
  - (2) the traditional notion of a *point* particle does not exist in string theory - an essential element in its ability to give ... a quantum theory of gravity.
- f. Riemann's geometrical framework, which relies fundamentally on distances between points, is modified on ultramicroscopic scales by string theory. p.234

  NOTE: In the ultamicroscopic realm, the extended nature of the string ensures that Riemann's geometry simply will not be the right mathematical formalism.
- g. Riemann's geometry must be replaced by the quantum geometry of string theory

3. A Cosmological Playground
   - a. Astronomers and astrophysicists are experimentally trying to answer whether cosmic [expansion will] continue forever or slow to a halt, reverse itself [and] lead to a cosmic implosion.
   - b. The answer [depends upon] the average density of matter in the universe
     - (1) If the average matter density exceeds a so-called *critical density* ... then a large enough gravitational force will permeate the cosmos to halt and reverse the expansion.

       NOTE: *critical density* [is] about a hundredth of a billionth of a billionth of a billionth (10^{-29}) of a gram per cubic centimeter
     - (2) If the average matter density is less than the critical value, gravitational attraction will be too weak to stop the expansion, which will continue forever.
   - c. ... there is a lot of nearly empty space between the galaxies that drastically lowers the overall average matter density. p.235
   - d. ... the average amount of visible matter in the universe ... [is] significantly less than the critical value. But there is strong evidence ... that the universe is permeated with *dark matter* (i.e. matter that does not participate in the processes of nuclear fusion that powers stars, does not give off light [and] is invisible to astronomers' telescopes].

(1) Just for argument sake assume that the mass density does exceed the critical value and that in a distant future the expansion will stop and the universe will begin to collapse ... into an ever shrinking cosmic mass ... to ... a final inexorable cosmic crunch [of] *no size at all.*

(2) When the distance scales involved are around the Planck length or less, quantum mechanics invalidates the equations of general relativity [and one] must instead make use of string theory.

e. ... string theory modifies the picture ... [and] ... proclaims that the universe cannot be squeezed to a size shorter than the Planck length in any of its spatial dimensions p.236

(1) ... no matter how many *points* [one] pile[s] up on top of each other ... their combined volume is still zero

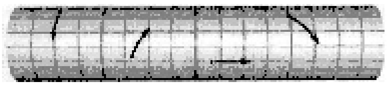
(2) by contrast, if these particles are really *strings*, collapsed together in completely random orientations, they will fill out a non-zero-sized blob, roughly like a Planck-sized ball of entangled rubber bands.

(3) ... string theory ... suggest[s] a minimum-size [to the] universe

f. To explain these important aspects ... first ... instead of considering all ten of the spacetime dimensions of string theory ... use the [two-dimensional] garden hose universe [illustration] ... to answer whether the geometrical and physical properties of this cosmic collapse have features that markedly differ between the universe based on strings and one based on *point* particles

4. The Essential New Feature p.237

a. A *point* particle moving in [a] two-dimensional universe can execute the kinds of motion illustrated in the figure to the right:

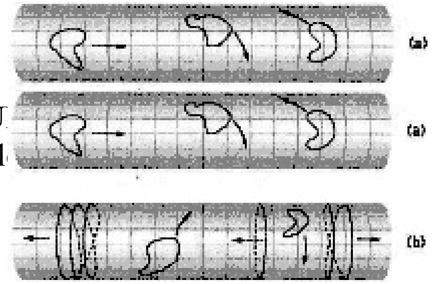


(1) it can move along the extended dimension of the garden hose

(2) it can move along the curled up part of the garden hose

(3) it can move along any combination of the two

b. A loop of string can undergo similar motion, with one difference being that it oscillates as it moves around on the surface ... imbu[ing] it with characteristics such as mass and force charges. (U



c. [There is] another difference between *point*-particl difference directly dependent on the *shape* of the space through which the string is moving: since the string is an extended object ... it can *wrap around* (lasso, so to speak) the circular part of the garden hose universe (sliding around and oscillating any number of times) in a *winding mode* of motion. (WRAPPED)

NOTE: a winding mode is a possibility inherent to strings but there is no point-particle counterpart

5. The Physics of Wound Strings p.238

a. ... a wrapped string has a *minimum* mass determined by the size of the circular motion and the number of times it wraps around.

NOTE: the string's oscillatory motion determines a contribution in excess of this minimum.

(1) a wound string has a minimum length determined by the circumference of the circular dimension and the number of times the string encircles it.

(2) the minimum length of a string determines its minimum mass: the longer

this length, the greater the mass, since there is more of it.
        (3) the energy bound in a wound string is proportional to the radius of the circular dimension
            (a) unwrapped strings also have a tiny minimum length since if they didn't [consideration would be about] *point* particles
            (b) [one could conclude] that even unwrapped strings have a minuscule yet nonzero minimum mass ... but the quantum mechanical effects ... are able to exactly cancel this contribution to the mass. (cf. Chapter 6 above)
            (c) this is how ... unwrapped strings can yield the zero-mass photon, graviton, and the other massless or near massless particles. p.239
            (d) wrapped strings are different in this regard.
    b. [the way in which] ... wrapped string configurations affect the geometrical properties of the dimension around which the strings wind ... is bizarre and remarkable.
    c. string theory claims that *all* physical processes in the garden-hose universe in which the radius of the circular dimension is shorter than the Planck length and is decreasing are absolutely identical to physical processes in which the circular dimension is longer than the Planck length and increasing.
    d. ... as the circular dimension tries to collapse through the Planck length and head toward even smaller size, its attempts are made futile by string theory, which turns the tables on geometry.
    e. string theory shows that this evolution can be rephrased - exactly reinterpreted - as the circular dimension shrinking down to the Planck length and then proceeding to expand.
    f. string theory rewrites the laws of short-distance geometry so that what previously appeared to be a complete cosmic collapse is now seen to be a cosmic *bounce*.
    g. the circular dimension can shrink to the Planck length but because of the winding modes, attempts to shrink further actually result in expansion.
       NOTE: the reason? See below

6. The Spectrum of String States
    a. The new possibility of wound-string configurations implies that the energy of a string/the energy in string configurations ... [in the garden-hose universe] comes from two sources whose contributions to the total energy of a string are generally different:
        (1) *vibrational motion* (having two categories):
            (a) *uniform/sliding vibrations* - the overall motion of string as it slides from one position to another without changing its shape
            (b) *ordinary/oscillating vibrations* - the usual oscillations already discussed (above)
        (2) and *winding energy*
    b. [both] ... depend on the geometry of the hose, that is, on the radius of its curled-up circular component, but with a distinctly stringy twist, since *point* particles cannot wrap around dimensions. p.240
    c. two essential observations ... establish that large values of the radius imply large winding energies and small vibrational energies, whereas small values of the radius implies small winding energies and large vibration energies
        (1) 1st, uniform vibrational excitations of a string have energies that are *inversely* proportional to the radius of the circular dimension (a direct

consequence of the quantum-mechanical uncertainty principle)

(a) a smaller radius more strictly confines a string and ... increases the amount of energy in its motion

(b) as the radius of the circular dimension decreases the energy of motion of the string necessarily increases

(2) 2nd, the winding mode energies are directly (not inversely) proportional to the radius (the minimum length of wound strings, and hence their minimum energy, is proportional to the radius)

(a) For any large circular radius of the garden-hose universe, there is a corresponding small circular radius for which the winding energies of strings in the former universe equal the vibration energies of strings in the latter, and vibration energies of strings in the former equal winding energies of strings in the latter.

(b) As physical properties are sensitive to the *total* energy of a string configuration, and not to how the energy is divided between vibration and winding contributions, there is *no physical distinction* between these *geometrically distinct* forms for the garden-hose universe (string theory claims that there is no difference whatsoever between a "fat" garden-hose universe and a "thin" [garden- hose universe]).

d. But ... certain pairs of distinct geometrical circumstances, leading to high-winding-energy/low-vibration-energy or low-winding-energy/high-vibration-energy, are *physically* indistinguishable (i.e. there is absolutely no physical distinction between the two string scenarios). p.242

NOTE: the number of times a string wraps around the circular dimension is called its *winding number*.

(1) the energy from winding, being determined by the length of wound string, is proportional to the *product* of the radius and winding number.

(2) ... for any amount of winding, the string can undergo vibrational motion.

(3) ... *uniform vibrations* ...have energies that are inversely dependent on the radius [and] are proportional to whole-number multiples of the *reciprocal* of the radius p.243

NOTE: the whole number multiple is called *vibration number*

e. The total energy carried by a string can be calculated in terms of its vibration number, its winding number, and the radius.

f. ... [there are] infinite possibilities for winding/vibration numbers that a string can assume. p.244

g. ... beyond *winding energy* ... consider energy contributions arising from the *uniform-vibrational motions* and *ordinary vibrations* of a string ... [which] give additional contributions to the string's total energy and also determine the force charges it carries. p.246

h. ... these contributions do not depend on the size of the radius.

i. CONCLUSION:

(1) the masses and charges of particles in a garden-hose universe with radius R are identical to those in a garden-hose universe with radius I/R

(2) ... there is no way to distinguish physically these two geometrically distinct universes.

7. A Debate

a. ... physics is governed by the properties of the *fundamental ingredients* - the particle masses (energies) and the force charges they carry.

   - b. ... in the special circumstance when the two values for the radius are inversely related to one another ... then the allowed energies and charges are actually identical. p.247
   - c. whether the radius is R or 1/R, the ... properties for *the fundamental ingredients* in string theory is identical
   - d. Although the detailed description [one] might give for strings may differ (whether they are wound around the circular dimension, or the particulars of their vibrational behavior) the ... physical characteristics they can attain is the same
   - e. Therefore, since the physical properties of the universe depend upon these properties of the basic constituents, there is no distinction, no way to differentiate, between radii that are inversely related to one another.

8. Three Questions
   - a. Background (from what precedes above) p.248
     - (1) for simplicity, discussion has taken place in the garden-hose universe (restricted to one extended and one curled-up spatial dimension)
     - (2) for three extended spatial dimensions and six circular dimensions (the latter being the simplest of all Calabi-Yau spaces) the conclusion is exactly the same: each of the circles has a radius that, if interchanged with its reciprocal, yields a physically identical universe.
   - b. Three questions:
     - (1) 1st, what is this nonsense about two indistinguishable possibilities with different radii?
     - (2) 2nd, (if string theory does away with sub-Planck distances) why talk about circular dimensions with radii that are a fraction of the Planck length?
     - (3) 3rd, so what about the two-dimensional garden-hose universe - how does this add up when all dimensions are included?
   - c. In our universe, we observe the three spatial dimensions, each of which, according to astronomical observations, appears to extend for about 15 billion light years ... [but] nothing tells us what happens after that - i.e. whether they continue on indefinitely or perhaps curve back on themselves in the shape of an enormous circle ... wind[ing] up back at the initial starting point.
   - d. The familiar extended dimensions ... may ... also be in the shape of circles and hence [be] subject to the R and 1/R physical identification of string theory.
     - (1) ... if the familiar dimensions are circular then their radii must be about as large as ... 15 billion light-years ... and growing as the universe expands.
     - (2) If string theory is right, this is physically identical to the familiar dimensions being circular with incredibly tiny radii of about $1/R=1/10^{61} = 10^{-61}$ times the Planck length.
     - (3) *These are ... well-known familiar dimensions in an alternate description provided by string theory.*
     - (4) In fact, in this reciprocal language, these tiny circles are getting ever smaller as time goes by, since as R grows, 1/R shrinks. p.249
   - e. How can [such] possibly be true? (e.g. a speck of a universe be physically identical to the great expanse we view in the heavens?)

9. Two Interrelated Notions of Distance in String Theory
   - a. The most meaningful definitions in physics are those that are operational - i.e. definitions that provide a means, at least in principle, for measuring whatever is being defined.

b. String theory's surprising answer to how an operational definition of the concept of distance can be given:
   (1) 1988 physicists Robert Brandenberger and Cumrun Vafa pointed out that if the spatial shape of a dimension is circular, there are two different yet related operational definitions of distance in string theory
      (a) definition #1 uses strings that are not wound around a circular dimension p.250
      (b) definition #2 uses strings that are wound around a circular dimension
         NOTE: in a *point*-particle theory, for which there is no notion of winding, there would be only one such definition
   (2) the results of each procedure differ [and] can be understood by appealing to the uncertainty principle.
      (a) unwound strings
         i) can move around freely and probe the full circumference of the circle, a length proportional to R
         ii) by the uncertainty principle, their energies are proportional to 1/R
      (b) wound strings
         i) have minimum energy proportional to R
         ii) by the uncertainty principle ... they are sensitive to the reciprocal of this value, 1/R
   (3) if each is used to measure the radius of a circular dimension of space, unwound string probes will measure R while wound strings will measure 1/R (measuring distances in multiples of the Planck length)
   (4) each experiment has an equal claim to being the radius of the circle (consistent with string theory's claim that, using different probes, measured distance can result in different answers)
      NOTE: this property extends to all measurements of links and distances not just to determining the size of the circular dimension
   (5) the results obtained by wound and unwound string probes will be inversely related to one another

c. if string theory describes our universe, why have ... these two possible notions of distance ... not [been] encountered ... in day-to-day or scientific endeavors?

d. b/c one operational definition proves extremely difficult to carry out while the other [definition] proves extremely easy to carry out [thus, the easier approach has ... been carried out ... completely unaware of there being another possibility.

e. ... only one of the two approaches is technologically feasible. p.251

f. Putting issues of practicality aside, in the universe covered by string theory one is free to measure distances using either of the two approaches.
   (1) ... astronomers measure the "size of the universe" ... by examining photons that have traveled across the cosmos ...
   (2) if the three familiar spatial dimensions are in fact circular and ... string theory is right, astronomers using vastly different (and currently nonexistent) equipment, in principle, should be able to measure the extent of the heavens with heavy wound-string modes and find a result that is the reciprocal of this huge distance. (the universe being either huge or terribly minute)

10. A Minimum Size p.252

a. If one ... stick[s] to measuring distances ... using the lightest of the string modes instead of the heavy ones, the results ... will *always* be larger than the Planck length.
   NOTE: assuming the three extended dimensions to be circular [consider] the hypothetical big crunch ...
   (1) by using unwound string modes it is determined that the universe has an enormously large radius and ... is shrinking in time
   (2) as [the universe shrinks] these unwound modes get heavier and the winding modes get lighter
   (3) when the radius shrinks ... to the Planck length (when R takes on the value 1) the winding and the vibration modes have comparable mass
   (4) the two approaches to measuring distance become equally difficult to carry out and ... each would yield the same result since 1 is its own reciprocal.
   (5) as the radius continues to shrink, the winding modes become lighter than the unwound modes and ... [the winding modes] should now be used to measure distances.
   (6) ... this method of measurement yields *the reciprocal* of that measured by the unwound modes, *the radius is larger than one times the Planck length and increasing.*
      (a) ... R (the quantity measured by a unwound strings) shrinks to1and continues to get smaller
      (b) 1/R (the quantity measured by wound strings) grows to 1 and gets larger
   (7) the minimal value encountered is the Planck length
   (8) the crunch to zero size is avoided, as the radius of the universe as measured using light string-mode probes is always larger than the Planck length p.253
   (9) the radius, as measured by the lightest of string modes, decreases to the Planck length and then immediately starts to increase
   (10) the crunch is replaced by a bounce

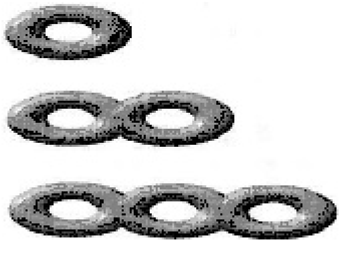
b. In the physical framework of string theory and, correspondingly, in the realm of the emerging discipline of quantum geometry, there are two notions of distance.

c. By judiciously making use of [them] both ... [a] concept of distance is found that meshes with ... intuition and with general relativity when distances are large, but that differs from them dramatically when distance scales get small (i.e. sub-Plank-scale distances are inaccessible).

d. Even if ...us[ing] the non-standard notion of distance and thereby describ[ing] the radius as being shorter than the Planck length, the *physics* ... encounter[ed] ... will be identical to that of the universe in which the radius, in the conventional sense of distance, is larger than the Planck length. p.254

e. Brandenberger, Vafa, and other physicists have made use of these ideas to suggest a rewriting of the laws of cosmology in which the Big Bang and the possible big crunch do not involve a zero-size universe, but rather one that is Planck-length in all dimensions - an appealing proposal for avoiding the mathematical, physical, and logical conundrums of the universe that emanates from or collapses to an infinitely dense point. Although it is conceptually difficult to imagine the whole of the universe compressed together into a tiny Planck-sized nugget, it is truly beyond the pale to imagine it crushed to a point of no size at all. String cosmology ... may very well provide ... this easier-to-swallow alternative to the standard Big Bang model.

11. How General Is This Conclusion?
    a. [it is unknown] ... whether the above conclusions about minimum spatial extent in string theory still hold if the spatial dimensions are not circular in shape
    b. the essential aspect of circular dimensions is that they permit the possibility of wound strings
    c. As long as the spatial dimensions ... allow strings to wind around them, most of the conclusions ... [above] should still apply.
    d. But ... if ... two of the dimensions are in the shape of the sphere ... strings cannot get “trapped”in a wound configuration, because they can always “slip off” (like a stretched rubber band pop[ping] off a basketball)
    e. Question: does string theory nevertheless limit the size to which these dimensions can shrink?
        (1) it depends on whether a full spatial dimension is being shrunk ... or ... an isolated “chunk” of space is collapsing.
        (2) the general belief among string theorists is that, regardless of shape, there is a minimum limiting size, much as in the case of circular dimensions, so long as ... a full spatial dimension [is being shrunk].
12. Mirror Symmetry p.255
    a. Einstein forged a link between the physics of gravity and the geometry of spacetime through general relativity.
    b. ... string theory strengthens and broadens the link between physics and geometry, since the properties of vibrating strings (their mass and the force charges they carry) are largely determined by the properties of the curled-up component of space.
    c. ... the geometry-physics association in string theory has some surprising twists
    d. In general relativity, and in “conventional” geometry, a circle of radius R is different from one whose radius is 1/R ... yet in string theory they are physically indistinguishable.
    e. [so ...] might there be geometrical forms of space that differ in more drastic ways ... in overall size ... in shape ... but that are ... indistinguishable in string theory?
    f. 1988 [physicists] Lance Dixon ... Wolfgang Lerche ... Cumrun Vafa, and Nicholas Warner ... suggest[ed] that it might be possible for two different Calabi-Yau shapes, chosen for the extra curled-up dimensions in string theory, to give rise to identical physics.
        (1) recall that the number of holes in the extra Calabi-Yau dimensions determines the number of families into which string excitations will arrange themselves (holes analogous to the holes one finds in a torus or its multihandled cousins) - but the two-dimensional figure on paper cannot show that a six-dimensional Calabi-Yau space can have holes of a variety of dimensions



        (2) the number of families of particles arising from string vibrations is sensitive only to the total number of holes, not to the number of holes of each particular dimension p.256
            (a) ... imagine ... two Calabi-Yau spaces in which the number of holes in various dimensions differs, but in which the total number

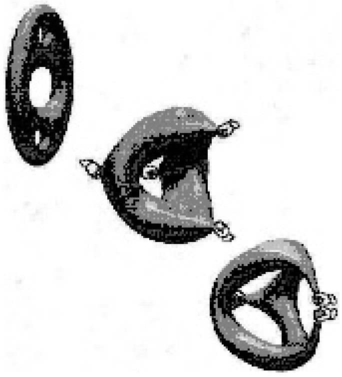
of holes is the same

(b) since the number of holes in each dimension is not the same, the two Calabi-Yaus have different shapes

(c) but since [the Calabi-Yaus] have the same total number of holes, each yields a universe with the *same number of families.*

g. the *orbifolding* technique (pioneered by Lance Dixon, Jeffrey Harvey ... Cumrun Vafa, and Edward Witte) is a procedure in which different points on an initial Calabi-Yau shape are glued together according to mathematical rules that ensure that a new Calabi-Yau shape is produced. p.257

h. if particular groups of points are glued together in just the right way, the Calabi-Yau shape ... produced differs from the [original one] in a startling manner: the number of *odd*-dimensional holes ... equals the number of *even*-dimensional holes in the original and vice versa.



i. the total number of holes (and therefore the number of particle families) in each is the *same* even though the even-odd interchange means that their shapes and fundamental geometrical structures are quite different p.258

j. beyond the number of families of particles, two different Calabi-Yau spaces also agree on the rest of their physical properties

k. for mathematical reasons having to do with the even-odd interchange, Brian Greene and Ronen Plesser coined the term *mirror manifolds* to describe the physically equivalent yet geometrically distinct Calabi-Yau spaces (i.e. [although] they have different geometrical properties, they give rise to one and the same physical universe when used for the extra dimensions in string theory).

l. Drastically different geometrical shapes that would imply different physical properties in general relativity [give] rise to identical physics in string theory.

m. ... all of the resulting physics in a mirror pair [are] identical p.259

13. The Physics and the Mathematics of Mirror Symmetry

a. The loosening of Einstein's rigid and unique association between the geometry of space and observed physics is one of the striking paradigm shifts of string theory.

b. *Mirror symmetry* ... provides a powerful tool for understanding both the physics of string theory and the mathematics of Calabi-Yau spaces.

c. ... *mirror symmetry* proclaims that particular pairs of Calabi-Yau spaces ... are ... intimately connected by string theory.

d. They are linked by the common physical universe each implies if either is the one selected for the extra curled-up dimensions.

(1) such provides an incisive new physical and mathematical tool

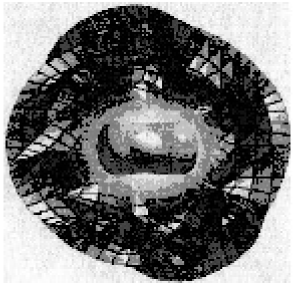
(2) Calabi-Yau [space] has a mirror partner p.260

(3) Since the resulting string physics associated with each member of the mirror pair is identical [one may] do calculations making use of either.

(4) From the perspective of one Calabi-Yau space, a calculation might involve an enormous number of difficult mathematical steps. By translating the calculation to its mirror, though, the calculation is reorganized in a far more efficient manner, allowing it to be completed with relative ease. p.261

(5) ... there have been many mathematical checks on the quantitative

reliability of the mirror symmetry of string theory [and] it has passed all with flying colors. p.262



(6) .. mathematicians have made great progress in revealing the inherent mathematical foundations of mirror symmetry (mathematical proof of the formulas used to count spheres inside Calabi-Yau spaces, thereby solving problems that puzzled mathematicians for hundreds of years).

(7) String theory not only provides a unifying framework for physics, but it may well forge an equally deep union with mathematics as well.

B. Chapter Eleven: Tearing the Fabric of Space p.263

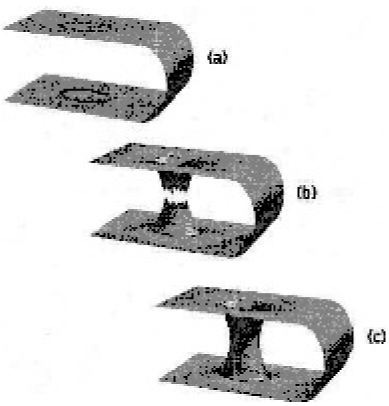
1. Introduction

a. Can the fabric of space rip apart?

(1) Einstein's general relativity says no.

- (a) the equations of general relativity are firmly rooted in Riemannian geometry and ... this ... framework ... analyzes distortions in the distance relations between nearby locations in space.
- (b) the underlying mathematical formalism requires that the substrate of space is *smooth* (no increases, no punctures, the separate pieces "stuck" together, and no tears).
- (c) for the fabric of space to develop such irregularities, the equations of general relativity would break down ...

(2) ... [some] quantum physic[ians] ... speculate that rips and tears might be a commonplace microscopic feature of the spatial fabric. p.264

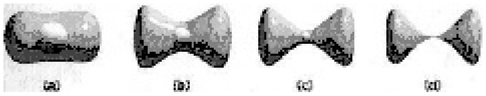


- (a) cf. the concept of *wormholes* (a bridge or tunnel providing a shortcut from on one region of the universe to another)
  - i) as in the drawings to the right (a) in a U-shaped universe the only way to get from one end to the others by traversing the whole cosmos
  - ii) the fabric of space (b) tears and two ends of a wormhole start to grow.
  - iii) the two wormhole ends merge together forming a new bridge or shortcut from one end of the universe to the other
  - iv) the wormhole creates *a new region of space* ... and ... blazes new spatial territory p.265
  - v) it is unknown if wormholes exist
- (b) cf. black holes are another example in which the fabric of space is stretched to its limits (the enormous gravitational field of a black hole results in such extreme curvature that the fabric of space appears to be pinched or punctured at the black hole's center) - the equations of general relativity break down under such

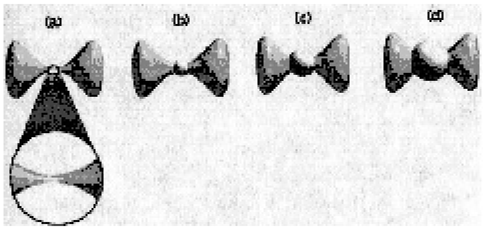
extreme conditions

  b. string theory ... shows that ... the fabric of space can tear p.266

2. A Tantalizing Possibility
  a. 1987 Shing-Tung Yau and ... Gang Tian ... found, using a well-known mathematical procedure, that certain Calabi-Yau shapes could be transformed into others by puncturing their surface and then sewing up the resulting hole according to a precise mathematical pattern.
    (1) they identified a particular kind of two-dimensional space (like the surface of a beach ball) sitting inside an initial Calabi-Yau space p.267
    NOTE: points on the ... surface can be located by giving two numbers (“latitude” and ”longitude”)
    (2) they considered shrinking the sphere so [the fabric of space] is pinched down to a single point



    (3) then they imagined tearing the Calabi-Yau space at the pinch, opening it up and gluing in another beach-ball like shape
  b. the pinched Calabi-Yau space tears open and grows a sphere that smooths out its surface (mathematicians call this sequence of manipulations a *flop-transition* - as if the original beach ball shape is “flopped”over into a new orientation within the overall Calabi-Yau space) p.268



  c. Under certain circumstances, the new Calabi-Yau shape produced by the flop is *topologically distinct* from the initial Calabi-Yau shape, (i.e. there is ... no way to deform the initial Calabi-Yau space into the final Calabi-Yau space without tearing the fabric of the Calabi-Yau space at some intermediate stage).
  d. In the realm of physics [this] raises a tantalizing question: ... beyond ... an abstract mathematical procedure ... might it be that, contrary to Einstein’s expectations, the fabric of space *can tear apart and subsequently be repaired* in the manner described?

3. The Mirror Perspective
  a. 1991 Norwegian physicist Andy Lutken ... with Paul Aspinwall ... asked ... “ if the spatial fabric of the Calabi-Yau portion of [the] universe were to undergo a space-tearing flop transition, what would it look like from the perspective of the mirror Calabi-Yau space?” p.269
    (1) review: the physics emerging from either member of a mirror pair of Calabi-Yau shapes (if selected for the extra dimensions) is identical, but the complexity of the mathematics ... to extract the physics can differ significantly between the two
    (2) Aspinwall and Lutken speculated that the mathematically complicated flop transition ... might have a far simpler mirror description - one that might give a more transparent view on the associated physics.
    (3) there did not seem to be anything in the mirror description that would indicate a disastrous physical consequence associated with the spatial tears of flop transitions
  b. 1991 a few string theorists had a strong feeling that the fabric of space *can* tear

4. Inching Forward (attempts to realize the mathematics of space-tearing flop transitions within the physics of string theory - a conclusion supported by mirror symmetry) p.270

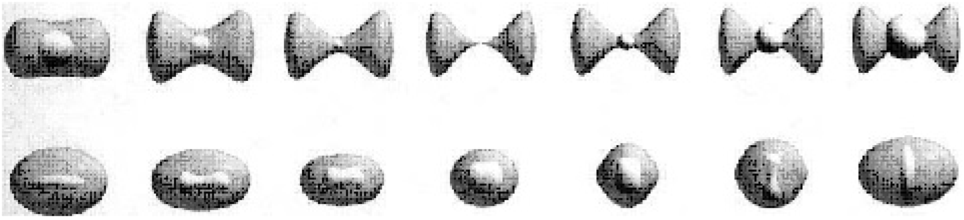
a. 1992 to prove that flop transitions can occur in string theory ... the required calculations ... were extraordinarily intensive ([and would take] more than a century to complete on the world's fastest computer)

b. 1992 Victor Batyrev [provided] a new idea ... that could greatly enhance the efficiency of ... calculational method ... he ... recast the construction of mirror manifolds in a more conventional mathematical framework ... and ... found a systematic mathematical procedure for producing pairs of Calabi-Yau spaces that are mirrors to one another p.271

c. ... [Batyrev's] methods ... [offered] a new line of attack on the issue of space-tearing flop transitions

5. A Strategy Emerges p.272

a. 1992 [Brian Greene, Paul Aspinwall and David Morrison] ... rephrase[d] the issue using the mirror description, hoping that the equations involved might be more manageable p.273



NOTE: [in the above schematic the top row is the original evolution from the figures on page 267 (above) and the bottom row is the same evolution from the perspective of the mirror Calabi-Yau shapes]

b. ... in ... mirror rephrasing ... it appears that string physics is perfectly well-behaved and encounters no catastrophes (i.e. there does not seem to be any pinching or tearing in the bottom row)

(1) QUESTION: was it true that at every step in the evolution to the right-hand side of the figure the physical properties of the original and mirror perspective are identical?

(a) ... [it was unknown] whether the upper and lower Calabi-Yau shapes continued to be mirrors after the tear has occurred

(b) ... absence of a catastrophe in the mirror perspective would mean an absence in the original ... demonstrat[ing] that space can tear in string theory

(2) this question [was] reduced to a calculation: extract the physical properties of the universe for Calabi-Yau shape after the tear [cf. upper right shape above] ... and for its supposed mirror [cf. lower right] ... and see if they are identical

6. Late Nights at Einstein's Final Stomping Ground p.274

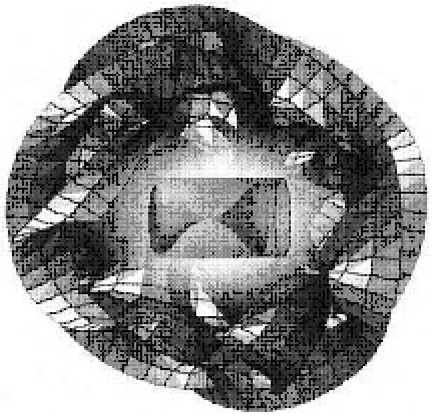
a. Greene, Aspinwall and Morrison split [their] calculation in two pieces:
NOTE: calculating the physics associated with the final Calabi-Yau shape in the upper row ... [was] straightforward p.275
NOTE: difficulty ...

(1) 1st, figuring out the *precise shape* of the final/mirror Calabi-Yau space in the lower row (see illustration above)

(2) 2nd, ... extracting the associated physics ...

b. They needed to ... find the *mathematical* form of the lower Calabi-Yau shapes that should correspond to the same *physical* universe as the upper Calabi-Yau shapes, if flop tears are within nature's repetoire.

7. Of Six-Packs and Working Weekends p.276
8. A Moment of Truth p.277
   a. The particular calculation ... roughly speaking ... [amounted] to determining the mass of a certain particle species (a specific vibrational pattern of the string) when moving through a universe [with an identified] Calabi-Yau component ...
   b. ... [it was] hoped ... that this mass would agree identically with a similar calculation done on the Calabi-Yau shape emerging from the space-tearing flop transition (the relatively easy calculation).
   c. [it was] shown that the supposed mirror is the mirror, and hence space-tearing flop transitions are part of the physics of string theory. p.278
9. Witten's Approach
   a. [Edward Witten also established] that flop transitions occur in string theory ... but his argument ... illuminate[d] the microscopic understanding of why the spatial tears do not have any catastrophic consequences.
      (1) His approach highlights the difference between a point-particle theory and string theory when such tears occur. p.279
      (2) The key distinction is that there are two types of string motion near the tear, but only one kind of point- particle motion.
      (3) a string can travel adjacent to the tear, like a point particle does, but it can also encircle the tear as it moves forward
   b. ... strings which encircle the tear (something that cannot happen in a point-particle theory) shield the surrounding universe from the catastrophic effects that would otherwise be encountered.
   c. It's as if the world-sheet of the string ... provides a protective barrier that precisely cancels out the calamitous aspects of the geometrical degeneration of the spatial fabric (see illustration on right).



      (1) But what if there is no string in the vicinity to shield a tear?
      (2) [cf. Feynman's formulation of quantum mechanics] ... an object, be a particle or a string, travels from one location to another by "sniffing out" all possible trajectories.
      (3) The resulting motion that is observed is a combination of *all* possibilities, with the relative contributions of each possible trajectory precisely determined by the mathematics of quantum mechanics. p.280
      (4) Should a tear in the fabric of space occur, then among the possible trajectories of traveling strings are those that encircle the tear ... numerous (infinite in fact) protective paths that encircle the tear ...
10. Consequences
   a. ... spatial tears can occur without physical calamity.
   b. If [one] could visualize six dimensional geometry, [one] would see that ... the fabric is tearing, but ... does so in a fairly mild way.
      (1) ... physical characteristics such as the number of families of string vibrations and the types of particles within each family are unaffected by

these processes.

(2) As the Calabi-Yau space evolves through a tear, what can be affected are the precise values of the masses of the individual particles - the energies of the possible patterns of string vibrations. p.281

(a) ... these masses will vary continuously in response to the changing geometrical form of the Calabi-Yau component of space, some going up while others go down.

(b) [but] there is no catastrophic jump, spike, or any unusual feature of these varying masses as the tear actually occurs (i.e. the moment of tearing has no distinguishing characteristics)

c. ... tears [can] also occur in the more familiar three extended spatial dimensions

(1) Space is space - regardless of whether it is tightly curled up into a Calabi-Yau shape or is unfurled into the grand expanse of the universe we perceive ...

(2) ... familiar spatial dimensions might themselves actually be curled-up into the form of a giant shape the curves back on itself, way on the other side of the universe, and ... therefore even the distinction between which dimensions are curled up and which are unfurled is somewhat artificial

d. ... such a topology-changing tear [could] happen today or tomorrow ... [or have happened] in the past

(1) [considering] the earliest epochs following the Big Bang, even non-string-based theories invoke important periods during which elementary particle masses do change over time

(2) from a string-theoretic perspective, these periods could certainly have involved the topology-changing tears discussed in this chapter

C. Chapter Twelve: Beyond Strings: In Search of M-Theory p.283

1. Introduction

a. If there is a final theory of nature, one of the most convincing arguments in supportive of its particular form would be that the theory couldn't be otherwise.

(1) i.e. the unique explanatory framework capable of describing the universe without running up against any internal inconsistencies or logical absurdities).

(2) i.e. things are the way they are because they *have* to be that way

b. inevitability erases options and leaves no other choices

c. Who or what made the seemingly insurmountable choices apparently required to design our universe? (... pursuit of such rigidity in the laws of nature lies at the heart of the unification program in modern physics) p.284

d. 1980s ... there were five different versions of string theory (see above notes from page 183 of the book) - differing both in how they incorporate supersymmetry and in significant details of the vibrational patterns they support.

e. This [was] an embarrassment for string theorists because although it's impressive to have a serious proposal for the final unified theory, having five proposals takes significant wind from the sails of each.

f. When physicists studied the equations of any one of the five string theories, they found that they *do* have many solutions ... with each solution corresponding to a universe with different properties. p.285

NOTE: most of these universes, although emerging as valid to solutions to the equations of string theory, appear to be irrelevant to the world as we know it

g. The equations of string theory are so complicated that no one knows their exact form (physicists have managed to write down only approximate versions of the equations [which]) differ significantly from one string theory to the next) ...

h. ... exact equations ... may resolve these problems ... [and] show that all five string theories are actually intimately related.

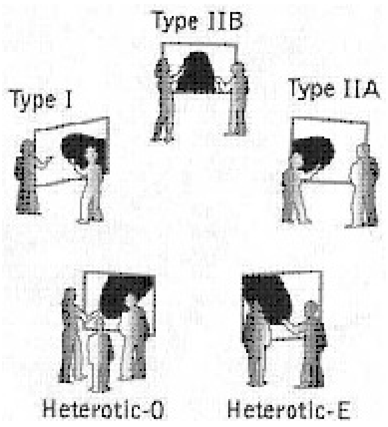
i. Rather than ... five distinctive string theories, physicists are ... convinced that there is *one* theory that sews all five into a unique theoretical framework.

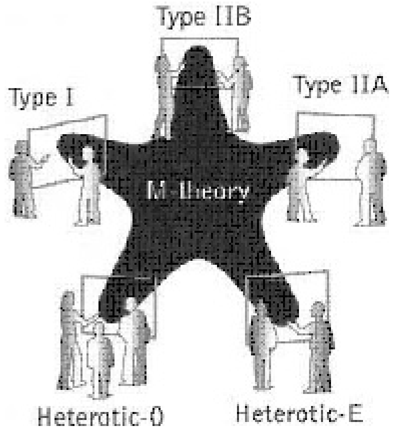
j. [so what is] ... the nature of the approximations used in studying string theory and their inherent limitations?

k. ... [one] must gain some familiarity with the clever techniques, collectively called *dualities*, that physicists have invoked to circumvent some of these approximations. And then ... follow the subtle reasoning that makes use of these techniques to find the remarkable insights alluded to above.

2. A Summary of the Second Superstring Revolution p.286

a. ... the five string theories were thought of as being completely separate. But, with the newfound insights emerging from recent research ... all of the string theories are now viewed as a single, all-encompassing framework ([with] a sixth theory merged into this union.





b. the overarching framework has provisionally been called M-theory (a landmark achievement in the quest for the ultimate theory) p.287

c. two essential features of M-theory

   (1) 1st, 11 dimensions (ten space and one time)

   (2) 2nd, vibrating strings, vibrating *two*-dimensional membranes, undulating *three*-dimensional blobs ("three-branes") and other ingredients ... p.288

d. Much of the true nature of M-theory remains mysterious ("M" theory for "mysterious")

3. An Approximation Method

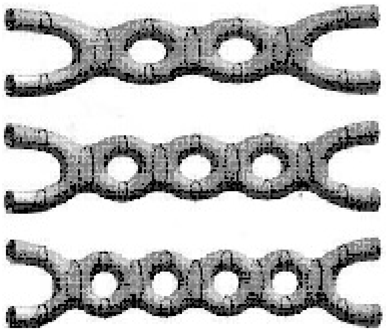
a. limitations of the methods ... us[ed] to analyze string theory are bound up with something called *perturbation theory* (i.e. making an approximation to try to give a rough answer to a question and then systematically improving [upon]/[refining] this approximation by paying closer attention to fine details initially ignored). EXAMPLE/ILLUSTRATION: a mechanic gives an initial estimate of the cost for repairing one's car and then gives the actual cost when the work is done

b. when perturbation theory is properly and effectively applied, the initial estimate will be reasonably close to the final answer p.289

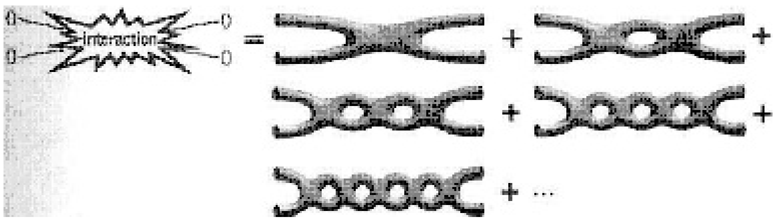
c. The incomplete understanding of string theory ... has its roots ... in this approximation method.

4. A Classical Example of Perturbation Theory
5. A Perturbative Approach to String Theory p.291
    a. Physical processes in string theory are build up from the basic interactions between vibrating strings (e.g. the splitting apart and joining together of string loops)
    b. ... a precise mathematical formula can be associated with the schematic portrayal (see diagram or the right) - [one] that expresses the influence that each incoming string has on the resulting motion of the other.

    c. ... the string/antistring pairs (two strings executing opposite vibrational patterns) can momentarily erupt into existence, borrowing energy from the universe, so long as they annihilate one another with sufficient haste, thereby repaying the energy loan.
    NOTE: these are known as *virtual string pairs* p.292
    d. (looking left to right on the diagrams) two initial strings slam together then merge into a single loop but frenzied quantum fluctuations result in the creation of a virtual string pair that travels along and then subsequently annihilates producing once again a single string that finally gives up its energy by dissociating into a pair of strings that head often in new directions
    e. ... quantum jitters can cause momentary virtual string eruptions to occur any number of times, producing a sequence of virtual string pairs



    f. ... string theorists have shown that [one] can understand the interaction between two strings by adding together the mathematical expressions for diagrams with no loops (no virtual string pairs), with one loop (one pair of virtual strings), with two loops (two pairs of virtual strings) etc. p.293
    g. The net influence each incoming string has on the other comes from adding together the influences involving diagrams with ever more loops.



    h. ... almost everything ... know[n] about string theory ... has been discovered ... [through] calculations using this perturbative approach. p.294
6. Is the Ballpark in the Ballpark?
    a. Although the mathematical formula associated with each diagram becomes very complicated as the number of loops grows, string theorists have recognized one basic and essential feature: (somewhat as the strength of a rope determines the likelihood that vigorous pulling and shaking will cause it to tear into pieces) there is a number that determines the likelihood that quantum fluctuations will cause a single string to split into two strings, momentarily yielding a virtual pair.

b. This number is known as *the string coupling constant*.
  (1) the size of the string coupling constant describes how strongly the quantum jitters of three strings (the initial loop and the two virtual loops into which it splits) are related ... how tightly… they are *coupled* to one another.
  (2) the calculated formalism shows:
    (a) that the *larger* the string coupling constant, the more likely it is that quantum jitters will cause an initial string to split apart (and subsequently rejoin)
    (b) [that] the *smaller* the string coupling constant, the less likely it is for such virtual strings to erupt momentarily into existence
    (c) the dividing line between "*small*" and "*large*" is the number 1 in the following sense: p.295
      i) if the string coupling constant has a value less than 1, then ... larger numbers of virtual string pairs are increasingly *unlikely* to erupt momentarily into existence (i.e. the loop diagram contributions become ever smaller as the number of loops grows)
      ii) if the string coupling constant [has a value of] 1 or greater, [then] it is increasingly *likely* that ever-larger numbers of such virtual pairs will momentarily burst on the scene (i.e. the loop diagram contributions become more important as the number of loops increases)
    (d) the process with no loops is *not* in the ballpark
c. [NO ONE KNOWS} ... the value of the string coupling constant (or ... the values of the string coupling constants in each of the five string theories)

7. The Equations of String Theory
  a. The perturbative approach for determining how strings interact with one another can also be used to determine the fundamental equations of string theory.
  b. ... the equations of string theory determine how strings interact and, conversely, the way strings interact directly determines the equations of the theory p.296
    (1) in each of the five string theories there is an equation ... meant to determine the value of the theory's coupling constant
      (a) Currently ... physicists have been able to find only an approximation to this equation, in each of the five string theories, by mathematically evaluating a small number of relevant string diagrams using a perturbative approach
      (b) a string coupling constant takes on a value such that if it is multiplied by zero the result is zero
      (c) in any of the five string theories, the approximate equation for its string coupling constant gives no information about its value
        i) b/c any number times zero yields zero
        ii) the equation can be solved with any value of the string coupling constant
    (2) in each of the five string theories ... another equation ... is supposed to determine the precise form of both the extended and the curled-up spacetime dimensions
    NOTE: [currently] the approximate version of this equation is far more restrictive than the one [just mentioned above] dealing with the string

coupling constant but ... still admits many solutions

c. Three [observations]

    (1) 1st, the as-yet-unknown exact form of these equations may admit a vast spectrum of solutions

        (a) [such] substantially weak[ens] their predictive power

        (b) [such] would be a setback, since the promise of string theory is that it will be able to explain these features the cosmos, rather than require [one] to determine them from experimental observation and, more or less arbitrarily, insert them into the theory

    (2) 2nd, the unwanted flexibility in the approximate string equations may be an indication of a subtle flaw in ... reasoning

        (a) perturbative methods are sensible only if the coupling constant is less than 1 p.297

        (b) [the] calculation may be making an unjustified assumption about its own answer (i.e. that the result will be smaller than 1)

        (c) perhaps, the coupling in any one of the five string theories is greater than 1

    (3) 3rd, the unwanted flexibility may be due to ... use of approximate rather than exact equations

        (a) [al]though the coupling constant in a given string theory might be less than one, the equations of the theory may still depend sensitively on the contributions from *all* diagrams

        (b) the accumulated small refinements from diagrams with ever more loops might be essential for modifying the approximate equations (which admit many solutions) into exact equations that are far more restrictive

d. 1990s [the 2nd and 3rd observations (above)] made it clear to most string theorists that complete reliance on the perturbative framework was standing in the way of progress - [a] breakthrough ... would require it a *non-perturbative* approach - [one] not shackled to approximate calculational techniques

8. Duality

a. 1995 Edward Witten's [presentation] to the strings conference at USC ... ignited the second superstring revolution ... [when he] announced a strategy for transcending the perturbative understanding of string theory ... [by using] the concept of *duality* p.298

    (1) *"duality"*: theoretical models appear to be different but nevertheless can be shown to describe exactly the same physics

        (a) "trivial" dualities (ostensibly different theories are actually identical and appear to be different only because of the way in which they happen to be presented)

        (b) "nontrivial" dualities (distinct descriptions of the same physical situation *do* yield different and complementary physical insights and mathematical methods of analysis) (there *are* important physical insights that follow from using these dual descriptions - such as a minimum size for circular dimensions and topology-changing processes in string theory)

            i) e.g. (Chapter Ten above) [through] string theory ... a universe that has a circular dimension of radius R can equally well be described as a universe with the circular dimension of radius 1/R (through the properties of string theory these distinct geometrical situations are actually physically identical) p.299

ii) e.g. mirror symmetry (two different Calabi-Yau shapes of the extra six spatial dimensions ... yield exactly the same physical properties (dual descriptions of a single universe)

(2) If two string theories differ with regard to significant details of their construction, it’s hard to imagine how they could merely be different descriptions of the same underlying physics.

(3) Nonetheless, through the subtle power of string theory, there is mounting evidence that all five string theories are *dual*. (Along with a sixth theory)

b. [duality] developments are intimately entwined with the issues regarding the applicability of perturbative methods

(1) the five string theories are manifestly different when each is *weakly coupled* (i.e. the coupling constant of the theory is less than 1)

(2) perturbative methods [rendered] physicists ... unable ... to address the question of what properties any one of the strings theories would have if its coupling constant should be *strongly coupled* (i.e. the coupling constant of the theory is larger than 1)

c. Witten and others ... suggest that (together with a sixth theory) ... the strong coupling behavior of any of these theories has a dual description in terms of the weak coupling behavior of another, and vice versa. p.300

d. [just as water can be liquid or solid] the string coupling constants play a role analogous to temperature - any two of the five string theories [may] at first ... appear to be completely distinct ... but as their respective coupling constants vary, the theories transmute among themselves

e. All of the string theories are dual descriptions of one single underlying structure

f. The reasoning underlying these results relies almost entirely on the use of arguments rooted in principles of symmetry.

9\. The Power of Symmetry

a. 1980s and 1990s physicists made ... progress in identifying certain special properties ... that are part of the strong-coupling physics of a given string theory, and yet are ... within [the] ability to calculate (w/calculations transcending the perturbative framework) ... [as] rooted in the power of symmetry p.301

b. Symmetry principles [include] ... the ... belief that the laws of physics do not treat any place in the universe or moment in time as special (i.e. the laws governing the here and now are the same ones that work everywhere and everywhen)

c. ... the power of symmetry is its ability to nail down properties in an *indirect* manner

d. [an integral part of string theory is the strong belief that] supersymmetry is a more abstract symmetry principle that relates physical properties of elementary constituents that carry different amounts of spin

(1) ... supersymmetry provides a sharp and incisive tool that can answer some very difficult and important questions by indirect means. p.302

(2) supersymmetry supplies ... constraining clues for those theories that incorporate its symmetry principles.

e. Based on the insights of E. Bogomol’nyi, Major Prasad and Charles Sommerfield, physicists have shown that this specification of a tight organizational framework (the framework of supersymmetry) and a *"minimality constraint"* (minimum mass for a chosen amount of electric charge) implies that the identity of the hidden contents is nailed down *uniquely*. (i.e. by ensuring that the content ... is the lightest it could possibly be and still have the specified charge, physicists showed that its identity is fully established). p.303

- f. Constituents of minimum mass for a chosen value of charge are known as *BPS* states (for the three discoverers mentioned above)
- g. re: *BPS states* - their properties are uniquely, easily, and exactly determined without resort to a perturbative calculation (regardless of the value of the coupling constants)
  - (1) even if the string coupling constant is large (implying that the perturbative approach is invalid) the exact properties of the BPS configurations can be deduced (*nonperturbative* properties)
  - (2) *BPS states* [can be euphemistically dubbed] *"**b**eyond **p**erturbative **s**tates"*

10. Duality in String Theory
  - a. EXAMPLE I: *Type I string*
    - (1) introduction
      - (a) imagine that all nine space dimensions are flat and unfurled)
      - (b) assume [that] the string coupling constant is much less than 1 p.304
        - i) thus, perturbative tools are valid
        - ii) thus, many detailed properties of the theory can and have been accurately worked out
      - (c) perturbative methods can still be used when increasing the value of the coupling constant but keeping it less than 1
        - i) detailed properties of the theory will somewhat change
        - ii) but the overall physical content of the theory remains the same, so long as the coupling constant stays in the perturbative realm
      - (d) increase the coupling constant beyond the value 1
        - i) perturbative methods become invalid
        - ii) thus, focus on *BPS states* (the limited set of nonperturbative masses and charges
    - (2) *strong coupling characteristics of Type I string theory exactly agree with known properties of Heterotic-O string theory, when the latter is a small value for its string coupling constant.*
      - (a) i.e. when the coupling constant of the Type I string is large, the particular masses and charges that we know how to extract are precisely equal to those of the Heterotic-O string when its coupling constant is small.
        - i) the physics of the Type I theory for large values of its coupling constant is identical to the physics of the Heterotic-O theory for small values of its coupling constant.
        - ii) related arguments [have] equally persuasive evidence that the reverse is also true - i.e. the physics of the Type I theory for small values of its coupling constant is identical to that of the Heterotic-O theory for large values of its coupling constant

            - (b) these two string theories which at first sight seem totally different (like liquid water vs. ice) are actually dual
            - (c) although the two string theories appear to be unrelated when analyzed using the perturbative scheme ... each transforms into the other ... as their coupling constants are varied in value
        - (3) *strong-weak duality*: the strong coupling physics of one theory is described by the weak coupling physics of another theory (i.e. the two theories involved are not actually distinct [but are] rather ... two dissimilar descriptions of the same underlying theory) p.305
            - (a) [if] the coupling constant of one member of a dual pair of theories is small, [one] can analyze its physical properties using well-developed perturbative tools
            - (b) [if] the coupling constant of one member of a dual pair of theories is large, [well-developed perturbative tools break down] [and one] can use of the dual description (in which the relevant coupling constant is small) and return to the use of perturbative tools
        - (4) the proposed duality provides a new tool for analyzing a strongly coupled theory: use perturbative methods on its weakly coupled dual description
        - (5) Most string theorists are convinced that the duality is true (although actually proving that the strong coupling physics of the Type I string theory is identical to the weak coupling physics of the Heterotic-O theory and vice versa ... has not yet been achieved b/c one member of the pair of the supposedly tool theories is not amenable to perturbative analysis [b/c] its coupling constant is too big).
    - b. EXAMPLE 2: Type IIB
        - (1) the Type IIB string is *self-dual* (i.e. as the coupling constant of the Type IIB string gets larger ... the physical properties ... appear to match up exactly with that of the weakly coupled Type IIB string itself) p.306
        - (2) if the Type IIB coupling constant were larger than 1, and its value was changed to its reciprocal (whose value is less than 1), the resulting theory is absolutely identical to the one with which one started
- 11. A Summary, So Far
    - a. (mid-1980s) Physicists constructed five different superstring theories wh/appeared to be distinct in the approximation scheme of perturbation theory
    - b. But the approximation scheme of perturbation theory is only valid if the string coupling constant in a given string theory is less than 1.
    - c. ... approximate equations currently available made calculation of the precise value of the string coupling constant in any given string theory impossible
    - d. Traditional perturbative methods give no insight into the strong coupling characteristics of any of the string theories
    - e. Using supersymmetry physicists learned how to calculate some of the strong coupling properties of a given string theory
    - f. The strong coupling properties of the Heterotic-O string appear to be identical to the weak coupling properties of the Type I string and vice versa.
    - g. The strong coupling physics of the Type IIB string is identical to its own properties when its coupling is weak.
- 12. Supergravity p.307
    - a. (1970s/1980s) Search for a unified theory of quantum mechanics, gravity, and the other forces in the framework of point-particle quantum field theory ...

[focused upon] theories with a great deal of symmetry - the most promising of which were those involving *supersymmetry*

b. *Supergravity* was the term coined to describe supersymmetric quantum field theories that tried to incorporate general relativity (but attempts to merge general relativity with quantum mechanics failed).

c. Attempts that came closest to success were supergravity theories formulated in more than four dimensions - the most promising being ten or a maximum of eleven dimensions.

d. 1984 with string theory the perspective on point-particle supergravity theories changed dramatically

e. with the precision currently available, examination of a string *looks* like a point particle

f. ... when studying low-energy processes in string theory (processes that do not have enough energy to probe the ultramicroscopic, extended nature of the string) [one] can approximate a string by a structureless point particle, using the framework of point-particle quantum field theory p.308

(1) this approximation cannot be used when dealing with short-distance or high-energy processes because ... the extended nature of the string is crucial to its ability to resolve the conflicts between general relativity and quantum mechanics that a point-particle cannot

(2) an approximation [for the sake of calculational convenience] can be made at low enough energies (large enough distances) [where] these problems are not encountered

g. The quantum field theory that most closely approximates string theory in this manner is ... ten-dimensional *supergravity*.

(1) [actually] there are four different ten-dimensional supergravity theories that differ in details regarding the precise way in which supersymmetry is incorporated

(2) QUESTION: what about eleven-dimensional supergravity (since string theory, formulate 10 dimensions, [*appeared]* to have no room for it?)

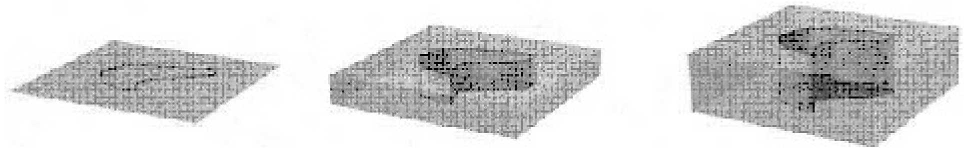
13. Glimmers of M-Theory

a. [at Strings '95 Edward Witten] argued that [if one starts] with the Type IIA string and increase[s] its coupling constant from a value much less than 1 to a value much greater than 1, the physics [one] is still able to analyze ... has a low-energy approximation that is eleven-dimensional supergravity (a theory specific to eleven dimensions [was] relevant to a different theory in ten) p.309

b. [Edward Witten and Petr Horava [later] found that] the strongly coupled Heterotic-E string also has an eleven-dimensional description.

(1) ... as the coupling constant is made larger a new "vertical" (tenth spatial) dimension becomes visible which, together with time, [leads to] eleven spacetime dimensions

(2) As the Heterotic-E string coupling constant is increased a new space dimension appears and the string itself gets stretched into a cylindrical membrane shape



(3) the structure of the Heterotic-E string changes as this dimension grows - stretched from a one-dimensional loop into a ribbon and then a deformed cylinder as the size of the coupling constant is increased p.310

c. the Heterotic-E string is *actually a two dimensional membrane* whose width is controlled by the size of the coupling constant

(1) for over a decade string theorists ... used perturbative methods ... firmly rooted in the assumption that the coupling constant is very small

(2) Witten [argued that] this assumption ... made the fundamental ingredients look and behave like one-dimensional strings even though they actually have a hidden, second spatial dimension

d. by relaxing the assumption that the coupling constant is very small and considering the physics of the Heterotic-E string when the coupling constant is large, the second dimension becomes manifest

(1) QUESTION: How does this mesh with the one time and nine space dimensions required by string theory?

(2) REVIEW (cf. Chapter Eight above): this constraint arises from counting the number of independent directions in which a string can vibrate and requiring that this number be just right to ensure that quantum-mechanical probabilities have sensible values

(3) ANSWER: the new dimension (cf. (2) above) is *not* one in which a Heterotic-E string can vibrate since it is a dimension ... locked within the structure of the "strings" themselves.

(a) the perturbative framework that physicists used in deriving the requirement of a ten-dimensional spacetime assumed from the outset that the Heterotic-E coupling constant is small.

(b) this implicitly enforced two mutually consistent approximations:

i) 1st, that the width of the membrane is small making it look like a string

ii) 2nd, that the 11th dimension is *so* small that it is beyond the sensitivity of the perturbative equations

(c) [thus] [one is] led to envision a ten-dimensional universe filled with one-dimensional strings

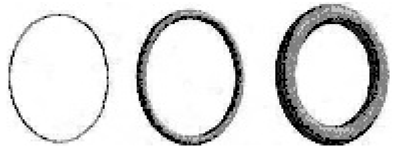
(4) it is now seen that this is but an approximation to an eleven-dimensional universe containing two-dimensional membranes

e. ... Witten first came upon the 11th dimension in his studies of the strong coupling properties of the Type IIA string

(1) there is an eleventh dimension whose size is controlled by the Type IIA coupling constant p.311

(2) when its value is increased, the new dimension grows [and] the Type IIA string expands into an "inner tube" (rather than stretching into a ribbon)

f. ... Witten argued that although theorists have always viewed Type IIA strings as one-dimensional objects (having only length but no thickness) this view is a reflection of the perturbative approximation scheme in which the string coupling constant is assumed to be small

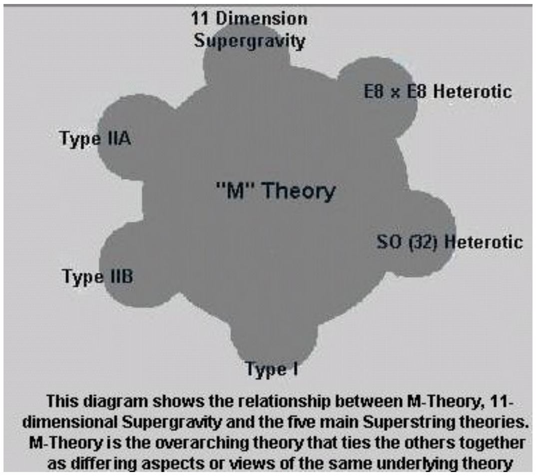


g. ... Witten's arguments and those of other physicists ... give strong evidence that the Type IIA and Heterotic-E "strings" are, fundamentally, two-dimensional membranes living in an eleven-dimensional universe.

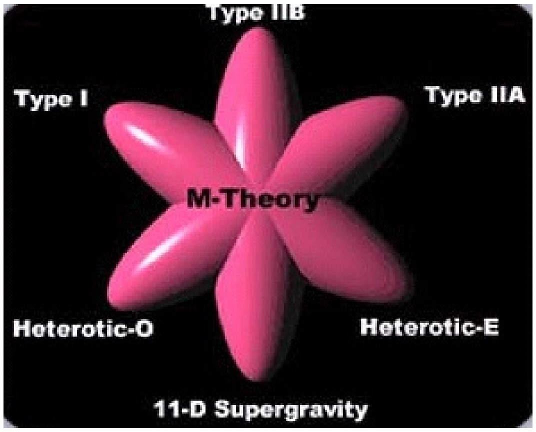
        (1) the eleven-dimensional theory (at low energies compared to the Planck energy) ... is approximated by the long-neglected eleven-dimensional supergravity quantum field theory
        (2) how to describe the eleven-dimensional theory (for higher energies) is currently under intense scrutiny
        (3) no one knows what this eleven-dimensional theory is ... [but] Witten has provisionally named it *M-theory* p.312
        (4) NOTE: the meaning of *"M-theory"* is unknown
            (a) Mystery Theory
            (b) Mother Theory (as in the mother of all theories)
            (c) Membrane Theory
            (d) Matrix Theory
        (5) ... but ... M-theory provides a unifying substrate for pulling together all five string theories

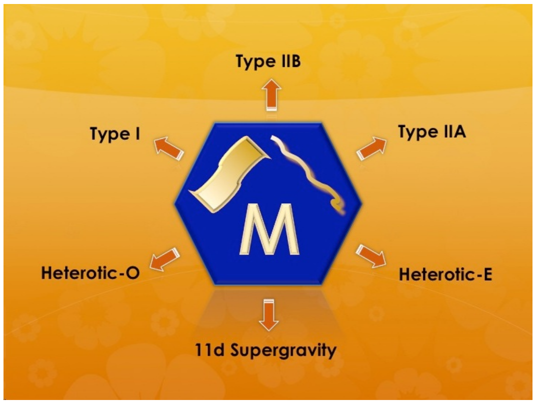
14. M-Theory and the Web of Interconnections
    a. Physicists have realized that M-theory is the unifying *pachyderm* of the five string theories (recall the old proverb about three blind men and their differing descriptions of an elephant)
    b. One aspect of the large/small circular radius duality that interchanges a circular dimension of radius R with one whose radius is 1/R was previously glossed over (cf. Chapter Ten above) but must now be clarified. p.313
        (1) the properties of strings in a universe with a circular dimension was discussed without carefully specifying which of the five string formations was being considered
        (2) it was argued that the interchange of winding and vibration modes of a string allows [one] to rephrase exactly the string theoretic description of the universe with a circular dimension of radius 1/R in terms of one in which the radius is R.
        (3) what was glossed over was that the Type IIA and Type IIB string theories actually get exchanged by this duality, as do the Heterotic-O and Heterotic-E strings .
    c. Precisely ... the physics of the Type IIA string in a universe with a circular dimension of radius R is absolutely identical to the physics of the Type IIB string in a universe with the circular dimension of radius 1/R.
       NOTE: a similar statement holds for the Heterotic-E and Heterotic-O strings
    d. This refinement of the large/small radius duality has important impact on the present discussion, i.e. by providing a link between the Type IIA and Type IIB string theories, as well as between the Heterotic-O and Heterotic-E theories, the large/small radius duality completes the web of connections
        (1) all five string theories, together with M-theory, are dual to one another [and] are all sewn together into a single theoretical framework p.314
        (2) the five different approaches describe one and the same underlying physics

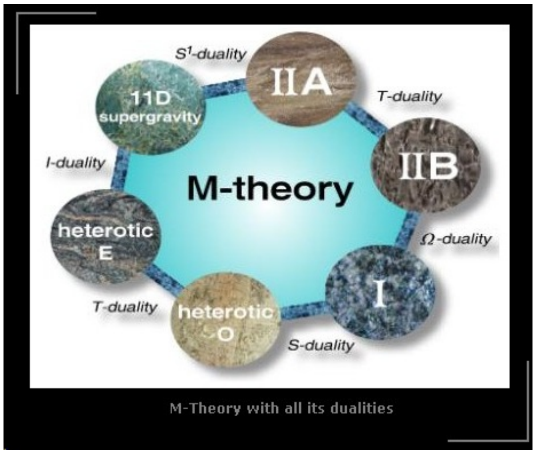
15. The Overall Picture
    NOTE: by incorporating the dualities, all five string theories, eleven-dimensional supergravity, and M-theory are merged together into a unified framework. p.315



This diagram shows the relationship between M-Theory, 11-dimensional Supergravity and the five main Superstring theories. M-Theory is the overarching theory that ties the others together as differing aspects or views of the same underlying theory







M-Theory with all its dualities

16. A Surprising Feature of M-Theory: Democracy in Extension
    a. When the string coupling constant is small in any but the supergravity peninsular region of the theory map, the fundamental ingredient of the theory appears to be a one-dimensional string.
    b. But ... each of the five string formulations involves two-dimensional membranes

p.316

    (1) This raises two questions:
        (a) 1st, are two-dimensional membranes the true fundamental ingredient of string theory?
        (b) 2nd, (regarding two-dimensional membranes) might it be that there are even higher-dimensional ingredients in the theory?
    (2) More is now known about *BPS states*
        (a) their masses
        (b) the force charges they carry
        (c) the way they *look*
            i) some are one-dimensional strings
            ii) some are two-dimensional membranes
            iii) some are three-dimensional, four dimensional … up to and including nine
    (3) String theory/M-theory (or whatever it is finally called) contains extended objects of a whole slew of different spatial dimensions
        (a) physicists have coined the term “three-brane” to describe extended objects with three spatial dimensions

            - (b) physicists have coined the term “four-brane” to describe extended objects with four spatial dimensions and so on up to nine-branes
            - (c) the fact that all of these extended objects are actually part of the theory has led Paul Townsend to declare a “democracy of branes” p.317
        - c. Physicists have shown that the mass of the extended objects of every dimension except for one-dimensional strings is *inversely* proportional to the value of the associated string coupling constant ... in any of the five string regions.
        - d. M-theory’s] fundamental ingredients are not just strings or membranes, but rather “branes” of a variety of dimensions, all more or less on equal footing ... [and] as [one] move[s] from the central region to any of the peninsular regions, only the strings (or membranes curled up to look ever more like strings) are light enough to make contact with physics as we know it ...
    - 17. Does Any of This Solve the Unanswered Questions in String Theory? p.318
        - a. Yes and no - the current scope of non-perturbative tools is quite limited ... [and] many issues remain unresolved.
        - b. [There is] a far deeper understanding of the logical structure and theoretical reach of string theory.
        - c. ... although the journey to strong coupling may [go] through unfamiliar regions of M-theory, it ultimately lands ... back in the comfortable surrounds of the weak coupling (albeit in the dual language of what was once thought to be a different string theory)
        - d. Duality and M-theory unite the five string theories ...
        - e. ... the string theorist can now claim with guarded optimism that the spectrum of logically sound theories incorporating the essential discoveries of the past century (special and general relativity; quantum physics; gauge theories of the strong, weak, and electromagnetic forces; supersymmetry, extra dimensions of Kaluza and Klein) is fully mapped out ... p.319
        - f. *the challenge to the string theorist (or perhaps the M-theorist) is to show that some point on the theory map [page 315 above] actually describes our universe*
            - (1) such will require finding the full and exact equations whose solution will pick out this elusive point on the map
            - (2) such will require corresponding physics with sufficient precision to allow comparisons with experiments
- D. Chapter Thirteen: Black Holes - A String/M-Theory Perspective p.320
    - 1. Introduction
        - a. The extreme physical conditions that occurred at the moment of the Big Bang and that prevail within black holes *cannot* be understood without a quantum mechanical formulation of the gravitational force.
        - b. But pre-string theory [evidenced a] conflict between general relativity and quantum mechanics
        - c. String theory [offers] a hope [for] solving this [conflict] (as well as [for] understanding ... black holes and the origin of the universe)
    - 2. Black Holes and Elementary Particles
        - a. Black holes (gargantuan) vs. elementary particles (minute) - not as different as initially thought?
        - b. except for a small number of distinguishing features all black holes appear to be alike p.321
            - (1) Demetrios Christodoulou, Werner Israel, Richard Price, Brandon Carter,

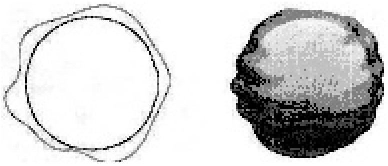
Roy Kerr, David Robinson, Stephen Hawking, and Roger Penrose [have] found increasingly persuasive evidence for what John Wheeler has summarized by the statement “black holes have no hair”

    - (2) distinguishing features
        - (a) the black hole’s mass
        - (b) the electric and certain other force charges a black hole can carry
        - (c) the rate at which a black hole spins
- c. any two black holes with the same mass, force charges, and spin are completely identical (i.e. there are not other intrinsic traits that distinguish one [black hole] from another)
  NOTE: It is precisely such properties (mass, force charges and the spin) that distinguish one elementary particle from another
- d. The similarity of the defining traits has led a number of physicists ... to the strange speculation that black holes might actually be gigantic elementary particles.
    - (1) According to Einstein’s theory [of general relativity] there is no minimum mass for a black hole.
    - (2) Crush a chunk of matter of any mass to a small enough size - it will become a black hole
    - (3) For small enough masses the black holes formed in this manner will look very much like elementary particles
- e. The catch: astrophysical black holes ... are so large and heavy that quantum mechanics is largely irrelevant and only the equations of general relativity need be used to understand their properties.
    - (1) however, the singular central point of collapse within a black hole [has a] tiny size [which] requires a quantum-mechanical description
    - (2) ... ever less massive black holes ... [reach] a point when they are so light and small that quantum mechanics *does* come into play (when total mass is at about the Plank mass or less)
    - (3) physicists who speculated that tiny black holes and elementary particles might be closely related ... ran up against the incompatibility between general relativity ... and quantum mechanics p.322

3. Does String Theory Allow Us to Go Forward?
    - a. [yes] string theory provides the first theoretically sound connection between black holes and elementary particles
        - (1) when six spatial dimensions are curled up into a Calabi-Yau shape, there are generally two kinds of spheres ... embedded w/in the shape’s fabric
            - (a) 1st, two-dimensional spheres
            - (b) 2nd, three-dimensional spheres ... w/*four* extended space dimensions
        - (2) [per the equations of string theory] ... it is likely possible that [over time] these three-dimensional spheres will shrink/collapse to vanishingly small volume p.323
        - (3) what if the fabric of space were to collapse in this manner?
        - (4) [initially] string theorists speculate[d] that if a three-dimensional sphere w/in a Calabi-Yau space were to collapse ... it might yield a cataclysmic result (e.g. the workings of the universe would grind to a halt)
        - (5) Andrew Strominger showed that doomsday speculations were wrong (b/c string theory is not just a theory of one-dimensional strings) p.324

(a) a one-dimensional string (i.e. one-brane) can completely surround a one-dimensional piece of space (like a circle)

(b) a two-dimensional membrane (i.e. two-brane) can completely surround a two-dimensional sphere (like plastic wrap around an orange)



(c) a three-dimensional membrane can completely surrounds a three-dimensional sphere ...

(6) Strominger showed that the wrapped three-brane provides a tailor-made shield that exactly cancels all of the potentially cataclysmic events ... previously feared to occur if a three-dimensional sphere were to collapse

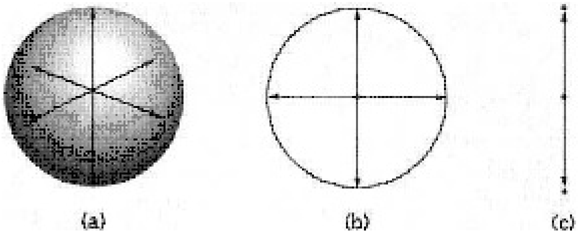
4. Tearing the Fabric of Space - with Conviction p.325

a. Strominger ... made use of ... string theory to resolve one of the thorniest issues surrounding the curling up of extra dimensions in a Calabi-Yau space ... [but such solved only half of the problem]

(1) ... he [noted] that when a three-dimensional sphere pinches down to a point ... the newfound extended objects in string theory ensure that physics continues to be perfectly well behaved

(2) but what about the tearing of space and its subsequent repair through the re-inflation of spheres?

b. Brian Greene and Dave Morrison ... realized that when a three-dimensional sphere collapses, it may be possible for the Calabi-Yau space to tear and subsequently repair itself by re-inflating the sphere ... but ... whereas the sphere that collapsed had three dimensions, the one that reinflates has only *two*



(1) [to understand this] imagine a *one*-dimensional sphere collapsing and being replaced by a *zero*-dimensional sphere `p.326

(2) [analogy]

(a) a two-dimensional sphere is the collection of points in three-dimensional space that are the same distance from a chosen center (see "a" in the above diagram)

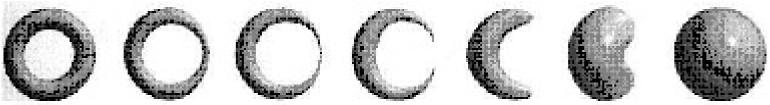
(b) a one-dimensional sphere [a circle] is the collection of points and two-dimensional space (e.g. the surface of this page) that are the same distance from a chosen center (see "b" in the above diagram)

(c) a zero-dimensional sphere is the collection of points in a one-dimensional space (a line) that are the same distance from a chosen center (this amounts to *two points* with the radius of the zero- dimensional sphere equal to the distance each point is from their common center) (see "c" in the above diagram)

c. After the collapse of a three-dimensional sphere inside a Calabi-Yau space, it seemed [to Greene and Morrison] that space could tear and subsequently repair itself by growing a two-dimensional sphere

(1) one Calabi-Yau shape could, in essence, transform itself into a

completely different Calabi-Yau shape ... while string physics remained perfectly well-behaved

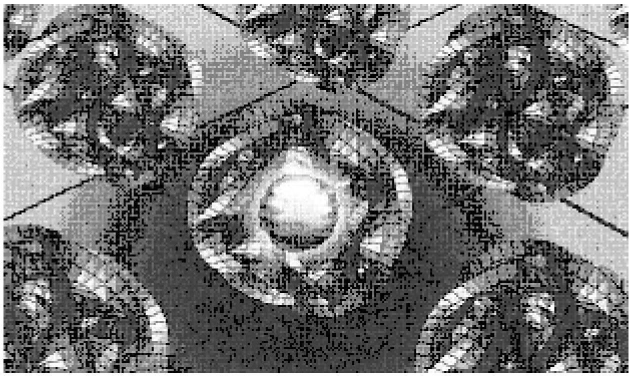


- (2) no singularities are introduced

5. A Flurry of E-Mail p.328

NOTE: [re: the dramatic new transformation of the spatial fabric that can follow the collapse of a three-dimensional sphere] - not only can the fabric of space undergo mild tears but ... far more drastic rips can occur as well p.329

6. Returning to Black Holes and Elementary Particles
   - a. What are the observable physical consequences of ... tears in the fabric of space?
     - (1) for flop transitions - not much happens at all
     - (2) for *conifold transitions* (technical term for drastic space-tearing transitions) - no physical catastrophe [is seen] but [there are] pronounced observable consequences
   - b. 1st, a three-dimensional sphere inside a Calabi-Yau space can collapse without an ensuing disaster because a three-brane wrapped around it provides a perfect protective shield



     - (1) to persons such as ourselves who are directly cognizant only of the three extended spatial dimensions, the three-brane "smeared" around the three-dimensional sphere will set up a gravitational field that looks like that of a black hole p.330
     - (2) someone looking through the extended dimensions ... will sense the wrapped-up brane by its mass and the force charges it carries, properties that ... look just like those of a black hole (cf. Gary Horowitz & Andrew Strominger)
     - (3) 1995 Strominger ... argued that the mass of the three-brane (the mass of the black hole) is proportional to the volume of the three-dimensional sphere it wraps:
       - (a) the bigger the volume of the sphere, the bigger the three-brane must be in order to wrap around it, and the more massive it becomes.
       - (b) the smaller the volume of the sphere, the smaller the mass of the three-brane that wraps it
       - (c) as this sphere collapses ... a three-brane that wraps around the sphere (perceived to be a black hole) is massless! (a massless black hole) p.331
   - c. 2nd, the number of holes in a Calabi-Yau shape (cf. Chapter 9) determines the number of low-energy, and hence low-mass, vibrational string patterns
     - (1) since space-tearing, *conifold transitions* change the number of holes ...

[one] expect[s] a change in the number of low-mass vibrational patterns

(2) Morrison, Strominger and Greene ... found that as a new two-dimensional sphere replaces the pinched three-dimensional sphere in the curled up Calabi-Yau dimensions, the number of massless string vibrational patterns increases by exactly one.

d. ... the new massless pattern of string vibration arising from the space-tearing conifold transition is *the microscopic* de*scription of a massless particle into which the black hole has transmuted.*

e. ... as a Calabi-Yau shape goes through a space-tearing conifold transition, an initially massive black hole becomes ever lighter until it is massless and then it transmutes into a massless particle ... which in string theory is nothing but a single string executing a particular vibrational pattern.

f. ... string theory explicitly establishes a direct, concrete, and quantitatively unassailable connection between black holes and elementary particles. p.332

7. “Melting” Black Holes

a. ILLUSTRATION OF “*PHASE TRANSITION*”: “phases” that transform from one form to another = “transition”
EXAMPLE(S):

(1) phase one: water as a solid (ice)

(2) phase two: water as a liquid (liquid water)

(3) phase three: water as a gas (steam)

b. Morrison, Strominger and Greene showed that there is a tight mathematical and physical analogy between such phase transitions and space-tearing conifold transitions from one Calabi-Yau shape to another

c. ... the kinds of black holes studied and the elementary particles are actually two phases of the same underlying stringy material/“two sides of the same coin” (i.e. the topological form (shape) of the extra Calabi-Yau dimensions determines whether certain physical configurations within string theory appear as black holes or elementary particles)

(1) phase 1: black holes

(2) phase 2: (black holes have gone through a phase transition and have “melted,” so to speak into) fundamental vibrational string patterns

d. The tearing of space through conifold transitions takes [one] from one Calabi-Yau phase to the other.

e. Black holes snugly fit within the framework of string theory

(1) recall ... that the five string theories are dual to one another and thereby are unified under the rubric of a single overarching theory p.333

(2) ... through ... space-tearing conifold transitions .. any given Calabi-Yau can continuously change into any other.

f. By varying coupling constants and curled-up Calabi-Yau geometry, [one sees] that all string constructions are ... different phases of a single theory.

8. Black Hole Entropy

a. ... [can] any of the other mysterious properties of our universe that have stubbornly resisted resolution for decades ... succumb to the power of string theory?

b. Foremost among these is the notion of *black hole entropy*.

(1) entropy: a measure of disorder or randomness (high entropy/disorder vs. low entropy/order) p.334

(2) [a] rigorous definition of entropy actually involves counting or

calculating the number of possible rearrangements of the microscopic quantum-mechanical properties of the elementary constituents of the physical realm that do not affect its gross macroscopic properties (such as its energy or pressure)

(3) ... entropy is a fully quantitative quantum-mechanical concept that precisely measures the overall disorder of a physical system.

c. 1970 Jacob Bekenstein ... [advanced] the remarkable idea that black holes might have entropy - and a huge amount of it.

- (1) his motivation: the 2nd Law of Thermodynamics (i.e. that the entropy of a system always increases/tends toward greater disorder)
- (2) [but] what happens ... near the event horizon of a black hole ... ? p.335
- (3) [he] reasoned that the only way to satisfy the second law of thermodynamics would be for the black hole to have entropy, and for this entropy to sufficiently increase as matter is pumped into it to offset the observed entropic decrease outside the black hole's exterior.
  - (a) Stephen Hawking had [already] shown that the area of *the event horizon* of a black hole (the surface of no return) always increases in any physical interaction (the total area of *the event horizon* always increases)
  - (b) to Bekenstein, the inexorable evolution to greater total area suggested a link with the inexorable evolution to greater total entropy embodied in the 2nd law of thermodynamics
- (4) [he] proposed that the area of the event horizon of a black hole provides a precise measure of its entropy

d. In the early 1970s w/o a way to merge general relativity and quantum mechanics, it seemed awkward, at best, to discuss the possible entropy of a black hole. NOTE: most physicists thought that Bekenstein's idea could not be right b/c:

- (1) 1st, black holes ... seem to be among the most ordered and organized objects in the whole universe
  - (a) black holes appear to lack sufficient structure to allow for disorder
  - (b) black holes seem too simple to support disorder
- (2) 2nd, entropy ... is a quantum-mechanical concept, whereas black holes (until recently) were firmly entrenched in the antagonistic camp of classical general relativity p.336

9. How Black is Black?

a. [Stephen] Hawking ... [initially] dismissed the analogy between his black hole area-increase law and the law of inevitable increase of entropy as nothing more than a coincidence.

- (1) tak[ing] the analogy between the laws of black holes and laws of thermodynamics seriously ... would ... force [one] to identify the area of the black hole's event horizon with entropy
- (2) one would also have to assign a *temperature* to the black hole (its precise value determined by the strength of the black hole's gravitational field at its event horizon)
  - (a) but if a black hole has a nonzero temperature (no matter how small) the most basic and well-established physical principles would *require* it to emit radiation, much like a glowing poker.
  - (b) but black holes ... are black ... supposedly ...not emit[ting] anything

    b. Hawking ... accept[ed] that if matter carrying entropy is dropped into a black hole, this entropy is lost, plain and simple (vs. the 2nd Law of Thermodynamics)
    c. [but] 1974 Hawking discovered [that] black holes ... are *not* completely black
        (1) that [by] only the laws of classical general relativity ... black holes ... do not allow anything (not even light) to escape their gravitational grip
        (2) but [that] the inclusion of quantum mechanics modifies this conclusion - black holes do emit radiation p.337
            (a) ... the uncertainty principle ensures that even the vacuum of empty space is a teeming, roiling frenzy of virtual particles momentarily erupting into existence and subsequently annihilating one another
            (b) This jittery quantum behavior also occurs in the region of space just outside the event horizon of a black hole.
    d. Hawking realized ... that the gravitational might of the black hole can inject energy into a pair of virtual photons ... that tears them just far enough apart so that one gets sucked into the hole ... the other photon ... [w/o] a partner with which to annihilate ... gets an energy boost from the gravitational force of the black hole ... get[s] shot outward ... [and] ... will appear as a steady stream of outgoing radiation [albeit meager ... and impossible to detect experimentally]
    e. Hawking ... calculate[d] the temperature that a far-off observer would associate with the emitted radiation and found that it is given by the strength of the gravitational field at the black hole's horizon, exactly as the analogy between the laws of black hole physics and the laws of thermodynamics suggested
    f. Bekenstein was right ... a black hole has entropy [enormous disorder] ... [and has temperature].
        (1) the less massive a black hole is, the higher its temperature and the greater the radiation in emits p.338
        (2) ... the more massive the [black] hole - the greater the entropy

10. Enter String Theory
    a. 1996 Strominger and Vafa ... use[d] string theory to identify the microscopic constituents of a certain class of black holes and to calculate precisely their associated entropy ... and the result ... agreed exactly with that predicted by Bekenstein and Hawking
        (1) they focused on a class of so-called *extremal* black holes (black holes that are imbued with charge ... and ... have the minimal possible mass consistent with the charge they carry) p.339
        (2) they ... systematically constructed (theoretical) black holes by carefully, slowly and meticulously weaving together a precise combination of the branes that had emerged from the second superstring revolution - maintaining full theoretical control over the microscopic construction of black holes ... [and] using string theory to account for the microscopic constituents and the associated entropy precisely p.340
    b. ... string theory has provided the first fundamental explanation of a long-established property of black holes that has stumped physicists using more conventional theories for many years ... [one that] is intimately tied up with Hawkins prediction that they should radiate ...

11. The Remaining [Two Central] Mysteries of Black Holes
    a. the 1st, [unresolved black hole mystery concerns] the impact black holes have on the concept of determinism

(1) ... if at some instant [one knew] the positions and velocities of every particle in the universe, [one could] use Newton's laws of motion to determine (at least in principle) their positions and velocities at any other prior or future time (i.e. any and all occurrences ... strictly follow from the precise positions and velocities of the particular ingredients of the universe a moment after the Big Bang) p.341

(2) [such] was substantially diminished by the discovery of quantum mechanics
   (a) ... Heisenberg's uncertainty principle undercuts Laplacian determinism because [one] fundamentally cannot know the precise positions and velocities of the constituents of the universe
   (b) ... these classical properties are replaced by quantum wave functions, which tell ... only the probability that any given particle is here or there, or that it has this or that velocity
   (c) but the concept of determinism is not left in total ruins
   (d) *quantum determinism* replaces Laplace's classical determinism
   (e) *quantum determinism* [states that] the probability that any particular event will occur at some chosen time in the future is fully determined by knowledge of the wave functions (the probability waves of quantum mechanics) of any prior time

(3) the probabilistic aspect of quantum mechanics significantly softens Laplacian determinism by shifting inevitability from outcomes to outcome-likelihoods ... fully determined within the conventional framework of quantum theory p.342

(4) 1976 Hawking declared that even this softer form of determinism is violated by the presence of black holes
   (a) when anything falls into a black hole, its wave function gets sucked in as well - [thus], in the quest to work out wave functions at all future times ... "vast enough" intelligence will be irreparably shortchanged [b/c] to predict the future fully [one] need[s] to know all wave functions fully today (but if some [wave function[s]] have escaped down the abyss of black holes, the information they contain is lost)
   (b) radiation carries energy and so, as a black hole radiates, its mass slowly decreases (it slowly evaporates ... [and] the distance from the center of the hole to the event horizon slowly shrinks)
   (c) regions of space that were previously cut off reenter the cosmic arena
   (d) does the information contained in the things swallowed by the black hole (data imagined to exist w/in the black hole's interior) re-emerge as the black hole evaporates?
      i) Hawking's answer: NO! (black holes destroy information ... introducing a new level of uncertainty into physics over and above the usual uncertainty associated with quantum theory) p.343
      ii) Stephen Hawking and Kip Thorne ... believe the information is forever lost
      iii) John Preskill believes YES! (the information reemerges as the black hole radiates and shrinks)

            - iv) Hawking recently acknowledged that the newfound understanding of black holes from string theory ... shows that there might be a way for the information to reemerge (information can be stored and recovered from the constituent branes)
    - b. the 2nd, [unresolved black hole mystery concerns] the nature of spacetime at the central point of the hole
        - (1) a straightforward application of general relativity ... shows that the enormous mass and energy crushed together at the black hole's center causes the fabric of spacetime to suffer a devastating rift, to be radically warped into a state of infinite curvature - to be punctured by a spacetime singularity
        - (2) one [possible] conclusion: time itself comes to an end at the heart of a black hole (since all of the matter that has crossed the event horizon is inexorably drawn to the center of the black hole, and since once there the matter has no future) p.344
        - (3) another [possible] conclusion: where time in our universe comes to an end, time in an attached universe just begins (the black hole's core might be a gateway to another universe that tenuously attaches to ours only at a black hole's center)
        - (4) it has not yet been settled what string theory has to say about the spacetime singularity at the center of the black hole
    - c. CENTRAL LESSON:
        - (1) extremes of huge mass and small size leading to unimaginable large density invalidate the sole use of Einstein's classical theory and require that quantum mechanics be brought to bear as well
        - (2) reliance on perturbative tools in string theory ... cloud [the] ability to analyze reliably and fully what happens at the deep interior point of a black hole
        - (3) [use of] nonperturbative methods ... may unravel the mysteries residing at the center of black holes

E. Chapter Fourteen: Reflections on Cosmology p.345

- 1. The Standard Model of Cosmology p.346
    - a. Introduction
        - (1) Einstein refused to take his own theory of general relativity at face value and accept [its implication] that the universe is neither eternal nor static
        - (2) Alexander Friedmann [accepted] Einstein's theory and found what is now known as the Big Bang solution to Einstein's equations (that the universe violently emerged from a state of infinite compression and is currently in the expanding aftermath of that primeval explosion)
        - (3) ... Friedman succeeded in convincing Einstein that there was no flaw in his work ... [so] Einstein ... retracted his objection
        - (4) Edwin Hubble ... confirmed that ... the universe is expanding
    - b. Summary: +/- 15 billion years ago the universe erupted from a ... singular event, which spewed forth all of space and all of matter ((for extensive details, see Wick's outline of Standard Hot Big Bang Cosmology)
    - c. How much faith should one really have in the Big Bang theory? p.347
- 2. Putting the Big Bang to the Test p.348
    - a. ... with their most powerful telescopes astronomers can see light that was

emitted from galaxies and quasars just a few billion years after the Big Bang ... [and can] verify the expansion of the universe predicted by the Big Bang theory back to this early phase of the universe (everything checks out to a "T")

b. To test that theory to yet earlier times, physicists and astronomers ... use ... more indirect methods - one of the most refined being ... *cosmic background radiation*

c. ... when things are compressed they heat up ... [and] reasoning in reverse, when things ... decompress/(expand) ... they cool down

d. ... the temperature of ... photon gas decreases as the universe expands

e. 1950s/1960s George Gamow ... Ralph Alpher ... Robert Hermann ... Robert Dicke and Jim Peebles ... realized that the present-day universe should be permeated by an almost uniform bath of these primordial photons, which, through the last 15 billion years of cosmic expansion, have cooled to a mere handful of degrees above absolute zero

f. 1965 Arno Penzias and Robert Wilson of Bell laboratories in New Jersey ... detected this afterglow of the Big Bang p.349

g. ... physicists and astronomers have confirmed to high precision that the universe is filled with microwave radiation ... whose temperature is about 2.7° above absolute zero - in keeping with the expectation of the Big Bang theory

h. This match between theory and experiment confirms the Big Bang picture of cosmology as far back as the time the photons first moved freely through the universe

i. By using standard principles of nuclear theory and thermodynamics, physicists can make definite predictions about the relative abundance of the light elements produced during the period of primordial nucleosynthesis

    (1) by measuring the helium abundance in stars and nebula, astronomers have amassed impressive support that this prediction is right on the mark.

    (2) perhaps even more impressive is the prediction and confirmation regarding deuterium abundance, since there is essentially no astrophysical process, other than the Big Bang, that can account for its small but definite presence throughout the cosmos

    (3) ... confirmation of these abundances, and more recently that of lithium, is a sensitive test of [the] understanding of early universe physics back to the time of their primordial synthesis

j. This is impressive almost to the point of hubris.

    (1) all the data ... confirm[s] a theory of cosmology capable of describing the universe from about 100th of a second ATB to the present p.350

    (2) [but] ... the newborn universe evolved with phenomenal haste

    (3) tiny fractions of a second ... form cosmic epochs during which long-lasting features of the world were first imprinted

    (4) physicists have continued to push onward, trying to explain the universe at ever earlier times

    (5) since the universe gets ever smaller, hotter, and denser as [one] push[es] back, an accurate quantum-mechanical description of matter and the forces becomes increasingly important

k. ... point-particle quantum field theory works until typical particle energies are around the Planck energy... (when the whole of the known universe fit within a Planck-sized nugget ... [having] a density so great ... at the Planck time [that it] was simply *colossal*

l. at such energies and densities gravity and quantum mechanics can no longer be treated as two separate entities as they are in point-particle quantum field theory

- m. at and beyond these enormous energies ... string theory must [be invoked] (THE CENTRAL MESSAGE OF THIS BOOK, The Elegant Universe)
- n. the earliest epoch ... is the cosmological arena of string theory (i.e. earlier than the Planck time of 10^{-43} seconds ATB)
- o. What does the standard cosmological theory convey about the universe before 100th of a second ATB but after the Planck time?

3. From the Planck Time to a Hundredth of a Second ATB
   - a. ... the three non-gravitational forces appear to merge together in the intensely hot environment of the early universe
     - (1) prior to about 10^{-35} seconds ATB, the strong, weak, and electromagnetic forces were all one “grand unified” or “super” force (a state in which the universe was far more symmetric than it is today)
     - (2) the significant differences between the forces as we now observe them were all erased by the extremes of energy and temperature encountered in the very early universe p.351
     - (3) *“symmetry breaking”*: as time went by and the universe expanded and cooled, the formalism of quantum field theory shows that this symmetry would have been sharply reduced ... leading to the [current] comparatively asymmetric form
     - (4) ... as ... the temperature of many physical systems [is lowered], at some point they undergo a phase transition that typically results in a decrease or “breaking” of some of their previous symmetries
     - (5) physicists believe that between the Planck time and a hundredth of a second ATB the universe ... pass[ed] through at least two ... phase transitions p.352
       - (a) at temperatures above 10^{28} Kelvin the three nongravitational forces appeared as one (symmetric)
         NOTE: as temperatures dropped below 10^{28} Kelvin the universe underwent a phase transition in which the three forces crystallized out from their common union (symmetry broken but not yet erased as the universe cooled)
         - i) their relative strengths and the details of how they act on matter began to diverge
         - ii) weak and electromagnetic forces were still deeply interwoven
       - (b) at 10^{15} Kelvin (and below) the universe went through another phase transition that affected the electromagnetic and weak forces (both crystallized out from their previous, more symmetric union and their differences became magnified)
     - (6) the two phase transitions are responsible for the three apparently distinct nongravitational forces at work in the world, even though this review of cosmic history shows that the forces, in fact, are deeply related
4. A Cosmological Puzzle
   - a. at the briefest of moments after the bang ... detailed questions are raised [which] while not invalidating the standard cosmological scenario as presented, do highlight awkward aspects that point toward the need for a deeper theory p.353
   - b. EXAMPLE: *the horizon problem* (one of the most important issues in modern

cosmology) ("*horizon*" refers to how far [it is possible to] see - how far light can travel, so to speak)

- (1) why does cosmic background radiation have temperatures so finely matched throughout vast differences of the universe/how can the uniformity of temperature throughout the vast expanse of the cosmos be explained?
- (2) [proposed] resolution: ... diametrically opposite places in the heavens (and everything else) that are far apart today ... [were] very close together during the earliest moments of the universe ... [so] it is not ... surprising that common traits such as temperature are shared
- (3) in the standard Big Bang cosmology the [above] suggestion fails
  - (a) spatial proximity ... [and] ... temporal duration [are at issue] - homogenization of temperature between two bodies relies on their having prolonged and unimpaired communication
    ILLUSTRATION:
    - i) a hot bowl of soup gradually cools to room temperature because it is in contact with the colder surrounding air
    - ii) eventually the temperature of the soup and the air will, through their mutual contact, become the same
    - iii) soup in a thermos ... [will] ... retain its heat for much longer ... [b/c] there is far less communication with the outside environment
  - (b) the speed of light sets a limit to how fast any signal or information of any kind can travel, [thus] matter in two regions of space can exchange heat energy and share a common temperature only if the distance between them at a given moment is less than the distance light can have traveled since the time of the Big Bang p.354
  - (c) ... [going] backward in time ... there is a competition between how close together ... spatial regions become vs. how far back ... the clock [is turned] for them to get there
    ILLUSTRATION:
    - i) for the separation of ... two spatial locations to be 186,000 miles [the clock would need to have ticked for] less than a second ATB ... [and] although they are much closer, there is ... no way for them to have any influence on each other since light would require a whole second to travel the distance between them
    - ii) for the separation of ... two spatial locations to be much less (e.g. 186 miles), [the clock would need to have ticked for] less than a thousandth of a second ATB ... [for again in less than a thousandth of a second light can't travel the distance between them
    - iii) etc.
- (4) in the standard Big Bang model ... just because two points in the universe get closer and closer ... [near to] the bang, it is not necessarily the case that they can have had the thermal contact ... necessary to bring them to the same temperature
- (5) detailed calculations show that there is no way for regions of space that are currently widely separated to have had the exchange of heat energy

that would explain their having the same temperature

(6) the puzzle does not mean the standard cosmological theory is wrong but the uniformity of temperature ... strongly suggest[s] [that an] important part of the cosmological story [is] missing

5. Inflation p.355

a. The root of the horizon problem is that in order to get two widely separated regions of the universe close together ... [one must go] back toward the beginning of time - so far back ... that there is not enough time for any physical influence to have traveled from one region to [another] (the universe does not shrink at a fast enough rate)

b. The dragging pull of gravity causes the expansion rate of the universe to *slow down* ... [and] ... less time since the bang (proportionally speaking) means it is harder for the two regions to communicate even though they get closer

c. Alan Guth [provided a] resolution for *the horizon problem*

(1) he found another solution to Einstein's equations in which the very early universe undergoes a brief period of enormously fast expansion - a period during which it "*inflates*" in size at an unheralded *exponential* expansion rate - getting faster as it proceeds

(2) [looking at the same situation in reverse] rapid accelerating expansion turns into rapid decelerating contraction

(3) thus, the two regions will have had more time to communicate thermally and ... will have had ample time to come to the same temperature

d. The standard cosmological model was revamped into *the inflationary cosmological model* (through Alan Guth's work and refinements made by Andrei Linde ... Paul Steinhardt ... and Andreas Albrecht) p.356

(1) the framework of the standard cosmological model is modified during a tiny window of time (10^{-36} to 10^{-34}seconds ATB) in which the universe expanded by colossal factor of at least 10^{30})

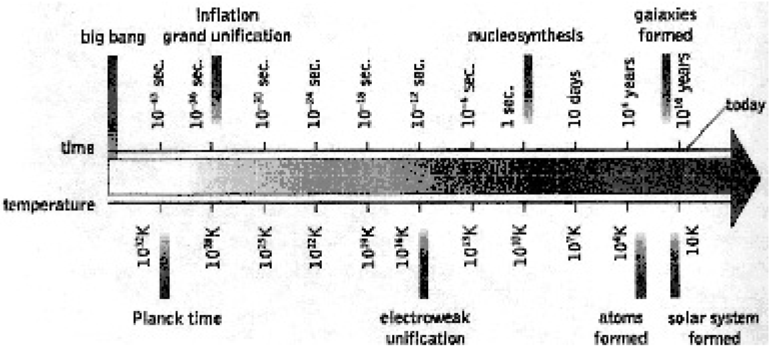
(2) in about a trillionth of a trillionth of a trillionth of a second ATB the size of the universe increased by a greater percentage that it has in the 15 billion years since

(3) before this expansion, matter that is now in far-flung regions of the cosmos was much closer together than in the standard cosmological model, making it possible for a common temperature to be easily established

e. The inflationary modification of the standard cosmological model solves the horizon problem (as well as a number of other important problems) and has gained wide acceptance among cosmologists.

6. Cosmology and Superstring Theory p.357

a. [another period of time] between the Big Bang and the Planck time [must] be discussed



    b. By blindly applying the equations of general relativity to that region, physicists have found that the universe continues to get even smaller, even hotter, and even denser as [one] move[s] backward in time toward the bang
    c. At time zero, as the size of the universe vanishes, the temperature and density soar to infinity, giving ... the most extreme signal that this theoretical model of the universe, firmly rooted in the classical gravitational framework of general relativity, has completely broken down.
    d. ... under such conditions general relativity and quantum mechanics must merge (i.e. string theory must be employed) - *string cosmology*
    e. string theory modifies the standard cosmological model in three essential ways:
        (1) 1st, string theory implies that the universe has what amounts to a smallest possible size [and] such has profound consequences for [an] understanding of the universe at the moment of the bang itself, when the standard theory claims that its size has shrunk all the way to zero
        (2) 2nd, string theory has a small-radius/large-radius duality (intimately related to its having a smallest possible size) which has deep cosmological significance
        (3) 3rd, string theory has more than four spacetime dimensions

7. In the Beginning Was a Planck-Sized Nugget p.358
    a. 1980s Robert Brandenberger and Cumrun Vafa made the first important strides toward understanding how ... string theoretic features modify] the conclusions of the standard cosmological framework.
    [Their] TWO IMPORTANT REALIZATIONS:
        (1) 1st, [looking backward in time] ... the temperature continues to rise until the size of the universe is about the Planck length in all directions
        (2) 2nd, [but then] temperature hits a *maximum* and begins to *decrease*
            (a) imagine for simplicity that all of the space dimensions of the universe are circular
            (b) running] the clock backward ... the radius of each of the circles shrinks, [and] the temperature of the universe increases
            (c) but as each of the radii collapses toward and then through the Planck length ... (within string theory) ...this is physically identical to the radii shrinking to the Planck length and then bouncing back toward increasing size
            (d) since temperature goes down as the universe expands ... the futile attempt to squeeze the universe to sub-Planck size means that the temperature stops rising, hits a maximum, and then begins to decrease
    b. Brandenberger and Vafa [presented] the following string theory cosmological picture:
        (1) in the beginning/at the beginning moment of the universe ...
            (a) all of the spatial dimensions ... are tightly curled up to their smallest possible extent, which is roughly the Planck length
            (b) temperature and energy are high but not infinite (avoiding the conundrums of an infinitely compressed zero-size starting point)
            (c) all the spatial dimensions ... are on completely equal footing (completely symmetric) - all curled up into a multidimensional, Planck-sized nugget
        (2) then the universe goes through its first stage of symmetry reduction when,

at about the Planck time, three of the spatial dimensions are singled out for expansion, while all others retain their initial Planck-scale size
- (a) these three space dimensions are then identified with those in the inflationary cosmological scenario
- (b) post-Planck-time evolution ... takes over
- (c) these three dimensions expand to their currently observed form p.359

8. Why Three? (what drives the symmetry reduction that singles out precisely three spatial dimensions for expansion?)
   - a. string theory provides a fundamental reason for why some [additional] number ... or all of the space dimensions don’t expand as well
   - b. Brandenberger and Vafa’s explanation:
     - (1) the small-radius/large-radius duality of string theory rests upon the fact that when a dimension is curled up like a circle, a string can wrap around it
     - (2) such wrapped strings tend to constrict the dimensions they encircle, keeping them from expanding ... but if the wrapped string and its anti-string partner ... should come into contact, they will swiftly annihilate one another, producing an *unwrapped* string
     - (3) if these processes happen with sufficient rapidity and efficiency, enough of the rubber band-like constriction will be eliminated, allowing the dimensions to expand
     - (4) the reduction in choking effect of wrapped strings will happen in only three of the spatial dimensions (reasons given below)
       - (a) imagine two point particles rolling along a one-dimensional line
       - (b) unless they ... have identical velocities, sooner or later one will overtake the other and they will collide
       - (c) but if they are randomly rolling around on a two-dimensional plane ... it is likely that they will never collide b/c the second spatial dimension opens up a new world of trajectories for each particle, most of which do not cross each other at the same point at the same time)
       - (d) in three, four, or any higher number of dimensions, it gets increasingly unlikely that the two particles will ever meet p.360
     - (5) ... an analogous idea holds if ... point particles [are replaced] with loops of string, wrapped around spatial dimensions (in four or more space dimensions, wrapped strings are less and less likely ever to collide)
9. Cosmology and Calabi-Yau Shapes
   - a. a circular shape is consistent with the [observed] universe ... so long as the circular dimensions are large enough that they curve back on themselves only beyond the range of our current observational capacity
   - b. for dimensions that stay small, a more realistic scenario is one in which [the dimensions] are curled up into a more intricate Calabi-Yau space
     - (1) through ... space-tearing conifold transitions ... any Calabi-Yau shape can evolve into any other p.361
     - (2) so [one] can imagine that in the tumultuous, hot moments after the bang, the curled up Calabi-Yau component of space stays small, but goes through a frenetic dance in which its fabric rips apart and reconnects over and over again, rapidly [going] through a long sequence of different

        Calabi-Yau shapes
    (3) As the universe cools and three of the spatial dimensions gets large, the transitions from one Calabi-Yau to another slow down, with the extra dimensions ultimately settling into a Calabi-Yau shape that ... gives rise to the physical features ... in the [observable] world

10. Before the Beginning?
    a. String theory allows [for one to address] persistent problems in the standard approach to cosmology
        (1) the whole notion of an initial singularity may be completely avoided by string theory
        (2) but, because of difficulties in performing fully trustworthy calculations in such extreme situations with [the] present understanding of string theory ... string cosmology ... is very far from the final word.
    b. Gabriele Veneziano and ... Maurizio Gasperini ... have ... their own ... version of string cosmology that shares certain features with the scenario described above, but also differs in significant ways. p.362
    c. they rely on string theory's having an minimal length in order to avoid the infinite temperature and energy density that arises in the standard and inflationary cosmological theories
    d. ... rather than concluding that ... the universe begins as an extremely hot Planck-sized nugget, [they] suggest that there may be a whole *prehistory* to the universe (starting long before ... time zero) that leads up to the Planckian cosmic embryo
    e. their so-called *pre-big bang* scenario
        (1) the universe began in a vastly different state than it does in the Big Bang framework
            (a) rather than being enormously hot and tightly curled into a tiny spatial speck, the universe started out as cold and essentially infinite in spatial extent
            (b) the equations of string theory then indicate that ... an instability kicked in, driving every point in the universe to rush rapidly away from each other - caus[ing] space to become increasingly curved and result[ing] in a dramatic increase in temperature and energy density
            (c) after some time, a millimeter-sized three-dimensional region within this vast expanse could look just like the super-hot and dense patch emerging from Guth's inflationary expansion
            (d) then through the standard expansion of ordinary Big Bang cosmology, this patch can account for the whole of the universe with which we are familiar
            (e) because the *pre-big bang* epoch involves its own inflationary expansion, Guth's solution to the horizon problem is automatically built into the pre-Big Bang cosmological scenario

11. M-theory and the Merging of All Forces p.363
    a. How does the strength of the gravitational force fit into the three non-gravitational couplings which merge together when the temperature of the universe is high enough?
    b. ...String theorists found that the mismatch could be avoided by carefully molding the shape of the chosen Calabi-Yau ... but such after-the-fact fine tuning always makes a physicist uncomfortable p.364

c. Within M-theory the strengths of all four forces can naturally merge.
  (1) by investigating how the strengths of the forces vary when the string coupling constant is not necessarily small, Witten found that the gravitational force curve can be gently nudged to merge with the other forces ... without any special molding of the Calabi-Yau portion of space
  (2) this may indicate that cosmological unity is more easily achieved by making use of the larger framework of M-theory

12. Cosmological Speculation and the Ultimate Theory
  a. Introduction
    (1) Modern science does not provide a connection between the question of *how* and the question of *why*
    (2) But ... cosmology ... at least allows for a scientifically informed view of the frame within which the questions are asked p.365
    (3) *Initial conditions* of the universe ... cosmological evolution and the state of the universe when it began can have a profound impact on the physics ... currently observe[d]
    (4) It is not known what the initial conditions of the universe were, or even the ideas, concepts, and language that should be used to describe them.
    (5) [but Greene] believe[s] that the outrageous initial state of *infinite* energy, density, and temperature that arises in the standard and inflationary cosmological models is a signal that these theories have broken down rather than [being] a correct description of the physical conditions that actually existed. p.366
    (6) ... no one has any insight on the question of how things actually did begin
    (7) ... [is] the question of determining the initial conditions ... one that is even sensible to ask ... is [it] a question that lies forever beyond the grasp of any theory?
    (8) ... attempts by physicists ... to bring the question of cosmological initial conditions within the umbrella of physical theory ... remain inconclusive
    (9) In the context of string/M-theory, ... cosmological understanding is, at present, just too primitive to determine whether our candidate “theory of everything” ... lives up to its name and determines its own cosmological initial conditions ... elevating them to the status of physical law.
    (10) ... some recent and highly speculative proposals have argued for yet other potential limits on the explanatory power of any final theory.
  b. *Andrei Linde’s Multiverse* (i.e. a vastly larger cosmological expanse, one of an enormous number of island universes scattered across a grand cosmological archipelago])
    (1) Linde has suggested ... that the brief but crucial burst of inflammatory expansion ... may not have been a unique, one-time event (i.e. conditions for inflammatory expansion may happen repeatedly in isolated regions ... throughout the cosmos, which then undergo their own inflationary ballooning in size, evolving into new, separate universes) - a *multiverse*)
    (2) ... consistent and uniform physics throughout our universe, ... may have no bearing on the physical attributes in these other universes ...
    (3) ... scan[ning] through this huge maze of universes, the vast majority will not have conditions hospitable to life, or at least to anything remotely akin to life as we know it
    (4) What is special about the particular combination of particle and force

properties we observe is that, clearly, they allow life to form. p.368

(5) ... things are the way they are in our universe because if they were not, we would not be here to notice (cf. *the anthropic principle*)
NOTE: *the anthropic principle* is a perspective that is diametrically opposed to the dream of a rigid, fully productive, unified theory in which things are the way they are because universe could not be otherwise

(6) The multi-verse hypothesis has the capacity to lessen our insistence on explaining why are our universe appears as it does

(7) Rather than being the epitome of poetic grace in which everything fits together with inflexible elegance, the multiverse and the anthropic principal paint a picture of a wildly excessive collection of universes with an insatiable appetite for variety.

(8) The concept of the multi-verse ... alert[s] [one] to the possibility [that one may be] asking too much of an ultimate theory

(9) ... [the] ultimate theory [should provide] a quantum-mechanically consistent description of all forces and all matter - a cogent cosmology

c. [Lee Smolin's] *cosmic version of genetic mutation* p.369

(1) (inspired by the similarity between conditions at the Big Bang and at the centers of black holes (each characterized by a colossal density of crushed matter) he has suggested that every black hole is the seed for a new universe that erupts into existence through a Big Bang-like explosion, but is forever hidden from our view by the black hole's event horizon.

(2) does an end run around the scientific limitations associated with the anthropic principle

VI. Part V: Unification in the Twenty-First Century p.371
Chapter Fifteen: Prospects (five central questions string theorists will face as they continue the pursuit of the ultimate theory) p.373

A. What Is the Fundamental Principle Underlying String Theory? p.374

1. symmetry/supersymmetry? p.375
2. Is string theory itself an inevitable consequence of some broader principle (possibly but not necessarily a symmetry principle) in much the same way that the equivalence principle inexorably leads to general relativity or that gauge symmetries lead to the nongravitational forces? (Currently: answer unknown)
3. ... a central organizing principle that embraces ... all ...features of the theory within one overarching and systematic framework ... is still missing. p.376
4. ... discovery of this principle would mark a pivotal movement in the developmental of string theory, as it would likely expose the theory's inner workings with unforeseen clarity.
5. There is ... no guarantee that such a fundamental principle exists, but ... string theorists ... have high hopes that it does.
6. ... finding [string theory's] ... "principle of inevitability" (that underlying idea from which the whole theory necessarily springs forth) is of the highest priority.

B. What Are Space and Time, Really, and Can We Do Without Them?

1. What is really meant by the *fabric* of the universe? p.377

a. ... [one] can still ask whether the geometrical model of spacetime that plays such a pivotal role in general relativity and in string theory is solely a convenient shorthand for the spatial and temporal relations between various locations, or whether [one] should view oneself as truly being embedded in *something* when [one] refers to [one's] immersion within the spacetime fabric.

b. ... string theory ... suggests an answer to this question: ... identify the fabric of spacetime itself with a colossal number of strings all undergoing the same, orderly, graviton pattern of vibration.

(1) ... such an enormous, organized array of similarly vibrating strings is known as a *coherent state* of strings p.378

(2) ... [the] ... meaning of strings ... as the threads of the spacetime fabric has yet to be worked out completely.

2. ... describing the spacetime fabric [in a] string-stitched form ... lead[s] ... to ... the question: Is there a raw precursor to the fabric of spacetime (a configuration of the strings of the cosmic fabric in which they have not yet coalesced into the organized form ... recognize[d] as spacetime)?

   a. ... in the raw state (before the strings that make up the cosmic fabric engaged in the orderly, coherent vibrational dance ...) *there is no realization of space or time* ... there is even no notion of *before*

   b. ... it's as if individual strings are "shards" of space and time (a structureless, primal state of existence - one in which there is no notion of space or time as we know it), and only when they appropriately undergo sympathetic vibrations do the conventional notions of space and time emerge.

   c. ... [how can one try to] envision a universe that "*is*" but does not invoke the concepts of space or time?

3. ... present formulation of string theory presupposes the existence of space and time within which strings (and other ingredients found in M-theory) move about and vibrate.

4. ... since the triumph of string theory is its natural incorporation of quantum mechanics and gravity, and since gravity is bound up with the form of space and time, [one] should not constrain this theory by forcing it to operate within an already existing spacetime framework ... rather ... allow string theory to *create* its own spacetime arena by starting in a spaceless and timeless configuration. p.379

   a. ... the hope is that from this blank slate starting point (possibly in an era that existed before the Big Bang or a pre-Big Bang ...) the theory will describe a universe that evolves to a form in which a background of coherent string vibrations emerges, using the conventional notions of space and time.

   b. Such a framework, if realized, would show that space, time, and, by association, dimension are not essential defining elements of the universe; rather, they are convenient notions that emerge from a more basic, atavistic, and primary state.

5. Research on aspects of M-theory (spearheaded by Stephen Shenker, Edward Witten, Tom Banks, Willy Fischler, Leonard Susskind and others) has shown that something known as *zero-brane* (possibly the most fundamental ingredient in M-theory, an object that behaves somewhat like a point particle at large distances but has drastically different properties at short ones) may give ... a glimpse of the spaceless and timeless realm.

   a. Their work has revealed that whereas strings show ... that conventional notions of space cease to have relevance below the Planck scale, the zero-branes give essentially the same conclusion but also provide a tiny window on the new unconventional framework that takes over.

   b. ... ordinary geometry is replaced by something known as *noncommunicative* geometry (cf. French mathematician Alain Connes) ... [in which] conventional notions of space and distance between points melt away.

   c. ... [but] on scales larger than the Planck length, physicists have shown that [the] conventional notion of space does reemerge. p.380

6. Finding the correct mathematical apparatus for formulating string theory without

recourse to a pre-existing notion of space and time is one of the most important issues facing string theorists.

7. An understanding of how space and time emerge would [be] a huge step [toward] answering the crucial question of which geometrical form actually does emerge.

C. Will String Theory Lead to a Reformulation of Quantum Mechanics?

    1. The universe is governed by the principles of quantum mechanics to fantastic accuracy.
    2. Even so ... physicists have followed a strategy that ... places quantum mechanics in a somewhat secondary position.
        a. In devising theories, physicists often start by working in a purely classical language that ignores quantum probabilities, wave functions, and so forth ... and then, subsequently, overlay[s] quantum concepts upon the classical framework.
        b. At first ... the universe appears to be governed by laws rooted in classical concepts such as a particle having a definite position and a definite velocity at any given moment in time [but] ... after detailed microscopic scrutiny ... [one] realize[s] that ... such familiar classical ideas must [be] modif[ied].... by quantum revelations.
    3. The mathematical formalism describing string theory begins with equations that describe the motion of a tiny, infinitely thin piece of classical thread .
    4. These equations are then *quantized* (i.e. classical equations are converted into a quantum-mechanical framework in which probabilities, uncertainty, quantum jitters, and so on are directly incorporated). p.381
    5. The strategy of beginning with a theoretical description that is classical and then subsequently including the features of quantum mechanics has been extremely fruitful for many years
    6. But it is possible, and ... likely, that this method is too conservative for dealing with theories that are as far-reaching as string theory and M-theory
    7. ... [in a] universe ... governed by quantum-mechanical principles ... theories ... should be quantum mechanical from the start.
    EXAMPLE: Duality
        a. through duality, one physical process can be described in a number of vastly different ways
        b. duality translations often take a process, described in one of the five string theories, that is *strongly* dependent on quantum mechanics ... and reformulate[s] it as a process that is *weakly* dependent on quantum mechanics from the perspective of one of the other string theories. p.382
        c. quantum mechanics is thoroughly intertwined within the duality symmetries underlying string/M-theory (they are inherently *quantum-mechanical symmetries* since one of the dual descriptions is strongly influenced by quantum considerations)
        d. ... the complete formulation of string/M-theory (a formulation that fundamentally incorporates the newfound duality symmetries) cannot begin classically and then undergo quantization, [as] in the traditional mold. (a classical starting point ... necessarily omit[s] the duality symmetries, since they hold true only when quantum mechanics is taken into account).
    8. ... it appears that the complete formulation of string/M-theory must break the traditional mold and spring into existence as a full-fledged quantum-mechanical theory ... [but] currently [it is unknown] how to do this.
    9. ... a reframing of the principles of quantum mechanics within string theory may yield a more powerful formalism that is capable of giving ... an answer to the question of how

the universe began and why there are such things as space and time - ... tak[ing] ... one ... closer to answering Leibniz's question of why there is something rather than nothing.

D. Can String Theory Be Experimentally Tested? p.383
  1. Three most important features of string theory must be kept in mind:
    a. 1st, gravity and quantum mechanics are part and parcel of how the universe works [so] any purported unified theory must incorporate both (as does string theory).
    b. 2nd, studies by physicists ... reveal that there are other key ideas (many of which have been experimentally confirmed) that appear central to [an] understanding of the universe (which emerge naturally from string theory)
    c. 3rd, *(unlike more conventional theories such as the standard model which has 19 free parameters that can be adjusted to ensure agreement with experimental measurements) string theory has no adjustable parameters.*
  2. In principle, [the] implications of [string theory] should be thoroughly definitive ... provid[ing] and unambiguous test of whether the theory is right or wrong (string theorists have sought and will continue to seek experimentally observable consequences of the theory)
    a. The confirmation of supersymmetry (through the discovery of super partner particles) would be a major milestone for string theory. p.384
    b. Supersymmetry is a central part of the theory [and] its experimental confirmation would be a compelling, albeit circumstantial, piece of evidence for strings.
    c. The masses and charges of the superpartner particles would reveal the detailed way in which supersymmetry is incorporated into the laws of nature.

E. Are There Limits to Explanation?
  1. Explaining everything ... is one of the greatest challenges science has ever faced and for the first time, superstring theory gives ... a framework that appears to have sufficient depth to meet the challenge.
    a. ... is there *no* explanation for these observed properties of reality? p.385
    b. ... is there a limit to comprehensibility/will aspects of the universe remain unexplained?
    c. are certain features of the universe the way they are because of happenstance accident or divine choice?
    d. ... is there an absolute limit of scientific explanation (issues that may never be resolved)?
  2. ... cosmology [plays a] role in determining the implications of an ultimate theory

F. Reaching for the Stars p.386
  1. One measure of the depth of a physical theory is the extent to which it poses serious challenges to aspects of ... worldview[s] that previously seemed immutable.
  2. With solid faith that the laws of the large and a small should fit together into a coherent whole, physicists are relentlessly hunting down the elusive unified theory.
  3. The search is not over, but through superstring theory and its evolution into M-theory, a cogent framework for merging quantum mechanics, general relativity, and the strong, weak, and electromagnetic forces has finally emerged.
  4. ... the challenges these developments pose to our previous way of seeing the world are monumental.
  5. The search for the fundamental laws of the universe is a distinctly human drama, one that has stretched the mind and enriched the spirit.
  6. We are all, each in our own way, seekers of the truth and we each long for an answer to why we are here ... as our generation marvels at our new view of the universe ... we are ... contributing our wrong to the human letter reaching for the stars.