Three Physics Paradigms– Newtonian, Relativistic, Quantum

This discussion is meant for a non-physics general audience, has has almost no equations

Newtonian Paradigm (NP)

NP is the oldest paradigm in physics that works and is what we mean by *Classical* physics. Appendix 1 provides details on its conceptual foundation. The concepts relate to things that humans can observe, from objects the size of sand grains to the solar system motion of planets, asteroids, comets, and human space exploration.

Fig 1A, the city scene from Australia's Sydney Harbor. The man-made items you use are due to the successful accuracy of NP calculations.

Bridges, complex buildings, vehicles, lighting, tall buildings, etc. – all are tributes to this brilliant work that began about 2 decades after the Jesuit Inquisition threatened Galileo to a fiery death.

Fig 1A Cities have complex structures in daily use.

NP allows us to include nearly every effect that we have observed, from mechanical friction and fluid viscosity to stresses in materials, the structure of planets, and ultimately to electric motors and combustion driven engines.

Fig 1B is the launch for a lunar landing, part of our human effort to understand the solar system and beyond. The image connects the beginning of NP (accurate descriptions of planetary orbits) to our modern explorations of this, our local patch of the Universe.

The success of modern astrophysics has been aided by using highly accurate telescopes, and other sophisticated optical applications. Optics is one of the foundation concepts the Newton included in his initial

Fig 1B Saturn V launch

In addition to making daily life more comfortable and interesting, NP is the underlying technique used to optimize our weapons of war. Kinetic weapons were used, and improved by trial and error for uncounted tens of thousands of years. Knives, spears, arrows, boomerangs, armor, catapults, and the host of explosive powered projectiles were operational long before Isaac Newton. But every one of these has been optimized by modern analysis. Modern kinetic kill weapons are vastly superior to prior to Newton's work.

It has been said that the Newtonian paradigm will never be proven *wrong*. It is extraordinarily accurate for human-sized conditions of our world. Certainly, no **theory** has ever proven it *wrong* nor could any do that. It has been shown to be only *inadequate* by **experimental tests** as we probe new sizes, speeds, masses, time durations, etc. Relativistic and Quantum concepts extend understanding outside the classical regime, and have proven applicability to previously unexplored conditions. But these do not *invalidate* NP in its region of applicability. In this same sense, relativity and quantum mechanics will never be *wrong*, either. It is strongly hoped, though, that they, too, will be extended by new ways of viewing the world about us, as we continue to explore new ways at looking at things.

Relativity Paradigm (RP)

In its general form, the Theory of Relativity describes the universe by combining the speed of light, simultaneity, geometry and gravitating clumps of mass. Its conceptual background is more fully discussed in Appendix 2.

Special (***SR***) Albert Einstein released the initial Special form in 1905, and extended NP to high velocities. *SR* appeared upon first reading to be a philosophical discussion of what "simultaneous" means to various observers; it did not "feel like" physics to NP physicists. It met with little understanding as very few physicists even tried to follow it. But *SR* works – it continually passes all experimental testing, and is now universally accepted. When quantum theory replaced its NP backbone with *SP*, the new merged theory yielded startling predictions with new and unexpected properties for the quantum worldview.

General (***GR***) Einstein released General Relativity, his expansion of *SR*, in 1915. *GR* added gravitational mass to *SR* basics, predicted the warping of space by local mass concentrations and used the theory to explain the astronomical universe. At almost the same time, he used *GR* to explain a vexing anomaly in the measured orbit of the planet Mercury. *GR* has never ceased to be tested for accuracy; its predictions have passed every test conducted.

Fig 2A illustrates that *GR* provides our foundation that allows us to understand the structure of Galaxies and of the Universe as a whole.

Fig 2A M31 Andromeda, our nearest galaxy neighbor. RP guides

Fig 2B is a space diagram showing the bending of space due to the mass of a star.

Concentric circular patterns show the gravitational energy well of the massive object. The further away from the star, the closer the well level is to the background gravitational effects from all the other mass in the universe.

Yellow curves are the paths light ray take when moving directly toward or away from the star. The path light between any two points gives the shortest time to travel that distance; Light paths define the geometry of space-time. Any light ray that passes near the mass follows the gravitational potential and is deflected by the well shape.

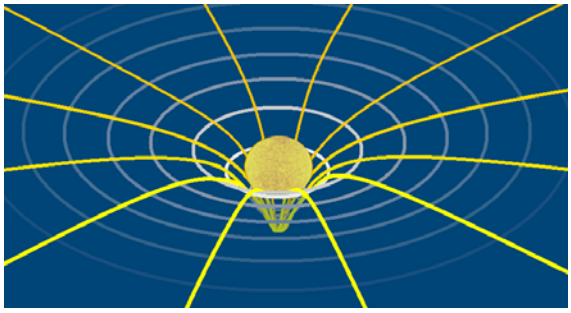

Fig 2B Relativity theory provides the tools to understand stellar dynamics

RP is in constant applied use –without it, our GPS location systems could not work, nor could we communicate with high velocity space craft far from Earth. Without it we could not be successful in modeling much that happens in the universe, or in the *micro*·verse domain of quantum theory.

GR successfully expanded *SR* to include gravitational effects, but is *incompatible* with quantum physics, even though *SR* is key to quantum success. The goal is to find a new paradigm that will successfully merge the two, but none of the proposed changes have proven successful … yet.

Quantum Paradigm (QP)

Details on the conceptual background of QP are found in Appendix 3.

Modern **quantum mechanics** (***QM***) describes an atom as a tiny positive central nucleus surrounded by a diffuse but definitely shaped cloud of negative electrons. It does not describe the exact current properties of any given electron because all electrons have exactly the same, completely indistinguishable except for physics properties such as energy and components of linear and angular momentum.

This means the QP is not a causal, deterministically predictive theory the way NP and RP are. The "diffuse but definite" cloud is called the probability density –the probability of any state is treated a an almost gaseous thing with varying density. But the probability gas requires a special kind of statistics that took decades to understand (if we actually do). This is the very best technique to describe and predict properties of materials, molecular interactions of chemistry and biology.

Fig 3A The calculated probability distribution of a specific atomic state

Fig 3A is an artists visualization of detailed computations of the probability wave function for a particular orbital electron distribution in an atom. It is a blurred solid in the murky probability background of all the general possibilities of its environment. Such calculations are tools that explain what we measure and deepen our understanding of how things work at the molecular, atomic, and smaller levels of reality.

Fig 3B pictures what *must* be happening, were we living in a deterministic atomic world. *Sizes and distances are not shown to scale*. The 2 electrons are in coulomb orbits due to their attraction toward the nucleus, similar to planets moving in gravitational orbits about the sun.
Two major differences between gravitational and electrostatic orbits –

1. Electrons repel each other, planets attract each other.
2. Coulomb orbits must radiate due to centripetal accelerations and cannot be stable. The classical model was corrected by adding waves and requiring wave stability; this accurately produced the basic quantum parameters for hydrogen. ***SR*** dynamics for elliptical orbits were added and the list of correct quantum parameters grew.

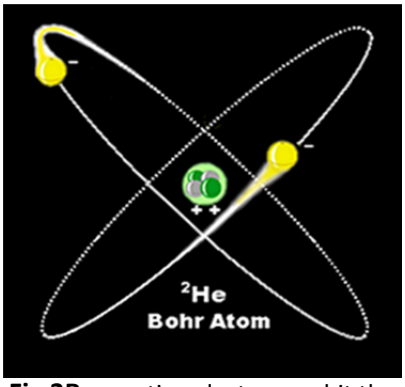

Fig 3B negative electrons orbit the positive nucleus in Old QM picture

This deterministic orbital model is called ***Old QM*** and gets many things right, *but also misses many things*. At least one website calls the orbit picture "***Wrong, Wrong, Wrong!"*** Instead, they *should* say that such images miss the probabilistic nature that is fundamental to our reality. **Fig 3B** is not exactly wrong, it is just **not right**. The complex probability wave distributions of modern *QM* are required for good predictions. *Even so – orbits are our best mental visualization of what is happening.* This is discussed more fully in our Appendix 3. Probability distributions for an electron would look nothing like the loops shown here.

QM, with its intrinsic probabilistic wave nature of matter, has been tested at least as fully as ***GR*** and has passed them all. Paul Dirac extended *QM* to electric fields using *SR* and formed the spectacularly accurate quantum electrodynamics (***QED***). *QED* was later extended to describe many different particles, but the extension needed logically questionable steps. The extension to all fundamental particles, called the Standard Model (***SM***), is actually accurate and necessary to our worldview. Nevertheless, most think it is neither complete nor sufficient.

For several reasons, the QP and RP are not consistent with each other. For nearly a century, many teams have worked on different paths toward a self-consistent "theory of everything" that agrees with observations. These conflicting hoped-for completions generate groups of true believers, our *physics denominations*.

Appendix 1 – Newtonian Paradigm

The conceptual basis for "Classical" Newtonian Physics, whose success is discussed in our main section

Isaac Newton (1643-1727) formulated his three Laws when, at age 22 (1665), he was isolated from the Black Death which was in the process of killing 1/3 of Europe. Newton solved then-current fundamental issues with planetary observations, and developed his physics (including optics) over the following two decades up when he published his magnum opus, *Principia*. He waited another 20 years to publish the calculus ideas he needed to devise his physics (and he only published after Leibniz in France independently developed the same ideas and *published*). Deep down, Isaac was a pious medieval man who spent much of his time investigating astrology as well as alchemy.
But Newton's physics is the oldest paradigm in physics that works; it is what is what we mean when we speak of classical physics.

Force is one of the concepts that must be defined by experience. Push or pull on a spring and you feel something stressing your hand. This "stress" from the spring is our starting point for the definition of *force*. Compress a spring a little bit and you must exert a little bit of effort. Push the spring to twice the compression and you feel yourself pushing twice as hard. Modern definitions are much more sophisticated in evaluating that "effort," but the concept of a *force* originates with the concept of an ideal spring.

1. Constant Motion When Isolated If no forces are applied to an object, its state of motion cannot change. This is the First Law as it is usually taught, but actually, it is a result of Law 2.

   This means that whatever its velocity happens to be *now*, it will remain the same at a later time. If it is unmoving compared to the landscape of its environment, it will not move. If it is moving, its velocity remain unchanging until a force is applied at any later time.

2. Velocity Changes When Force Is Applied If a force is applied to an object, its motion (velocity) must change in magnitude or direction, or both.

   This is the famous F = ma relation. Acceleration is the direct response to an applied force, and can be readily measured. *No* force means *no* acceleration which means *constant* velocity Actually, this is our first and most basic definition of mass. Mass "m" is the measured ratio of applied force to the object's acceleration.

   Acceleration means velocity is changing.

   $$m = \frac{\text{Force}}{\text{acceleration}}$$

3. Equal and Opposite Response To Force When a force is applied to an object, the mass's associated property, inertia, responds with a reactive force that is equal but opposite to the applied force.

These 3 NP laws form a set of relations that can be reworked to obtain the useful mathematical quantities of energy, momentum and all the properties of angular motion. During the 1800s, these derived concepts were embedded into the powerful Lagrangian and Hamiltonian techniques which form our sophisticated analysis tools.

Electro Dynamics In the 1860, James Clerk Maxwell merged NP with the non-mechanical properties of charge, current and magnets to form the highly mathematical unified view called electrodynamics. Electrodynamics has met all tests and is the basis for much of what we call the "modern" lifestyle.

Thermodynamics The concept of energy was formalized in the 1700s, when phlogiston and caloric proved to be inadequate descriptions of heat flow. During the 1800s, energy, work, power and temperature were made measurable, and the 3 laws of Thermodynamics were formulated. Probability and statistics were merged with NP analysis and the thermodynamics was then shown to be a fundamental branch of the Newtonian paradigm.

Newtonian Physics 2 —

Newtonian space. Newton solved the basic issue of planetary orbits by postulating that mass generated an attraction that worked without touching the affected other objects (which all have mass). This "action at a distance" concept was one of the may concepts that were were shocking to right-thinking people of the time.

NP includes the theory of optics, to which Isaac Newton contributed well. He showed that light was made up of various colors (wavelengths) that may be separated by various methods. He is responsible for reflective telescopes, called Newtonian reflectors. This is the progenitor of all modern large telescopes, and opened the universe to visual inspection. Many of his ideas of about light were superseded in the 18th and 19th centuries when the wave theory of optics became accepted. In Maxwell's merger (1860) of electricity and magnetism with NP made possible our understanding and usage of electromagnetic waves… radio, microwaves, infrared, visible, ultraviolet, x-rays, etc. He decided that light was composed of particles, "corpuscles," that traveled through the medium of aether. He later abandoned the mechanical aether idea, and decided his corpuscles traveled through divine processes. It is interesting that something like Newtonian corpuscles were merged with waves again in the early parts of the 20th century.

After a hundred years the general consensus on the NP was that the universe was composed of what we would call space and they called aether. Gravity operated through the medium of aether. Light was composed of electric and magnetic fields that rise and fall in precise relation with each other. When the oscillations separated from the source, they traveled through the aether as a disturbance, just as a water wave is a disturbance that travels across a pond.

Fig 4 shows the *NP* space, as people would have visualized it in the late 1800s. Picture the sun as the center of the solar system, with the circles and fine dotted radial grid showing the layout of the gravitational potential energy generated by the solar mass. This distribution of potential energy is the sun's gravitational field.

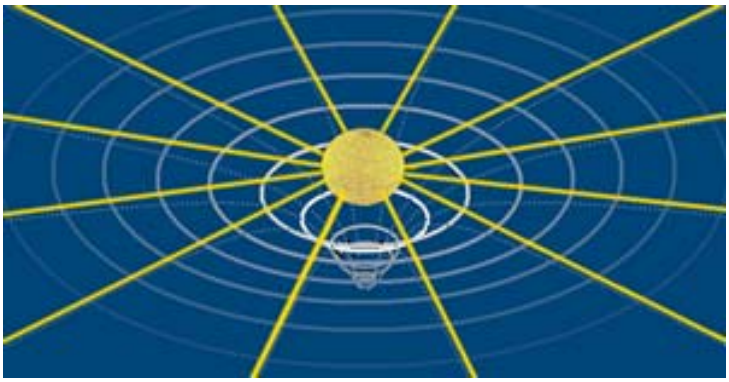

Fig 4: The sun's gravitational field is visualized by the distribution of energy needed to travel outwards. Light travels in straight lines from the sun outwards.

For an object to escape from the sun's surface, it must receive energy equal to the depth of the gravity well. This is usually accompanied by an external force of sufficient magnitude. The object would fall back down the gravity well if the energy were small, it would enter an orbit about the sun if it received more energy and a sideways velocity, or it would escape to infinity if the energy gained was the well depth. This picture works as well for escape from the surface of the Earth. Gravity wells form the Newtonian reality behind our rocket-driven space travel.

The Clockwork Universe ***Classical Physics*** provided the foundation for the 19th century development of modern concepts in energy, including thermodynamics, electrodynamics, and statistical dynamics. The core concept was that the future of Nature was completely determined (via the Laws) by all all of Nature's conditions *Now*. The Universe was like a gigantic mechanical clock with all its gears fully meshed together.
The Newtonian laws were perfect. Everything happens exactly as we calculate that they should …

… but then one day we found something that did not.

Appendix 2 – Relativistic Paradigm

The conceptual basis for Relativity Theory (RP) *, whose success is discussed in the main section*

Overall summary
- Any natural law must be stated the same way in all every frame of reference.
- The timing between events is relative to the specific reference frames.

Special Relativity (*SR*) 1905 Albert Einstein (1879-1955) published his theory of Special Relativity 1905, after about 10 years of development, and 1 year after Henri Poincaré published a similar analysis to explain previous experimental data. Einstein's work did not use that data and the theory bears his name because of the deep synthesis his ideas provided.

Results due to the Special Principle of Relativity —

> **Special Principle of Relativity**
>
> If A and B are two *reference frames* (basically, isolated chambers) in *uniform motion* (not accelerated) with respect to each other, no physical experiment whatever, can distinguish between them. These are called *inertial frames*.

Constancy of light In **every** *inertial* frame, the light speed c is is measured to be the same exact digits (the same numbers of meters/second). This is experimentally shown to be nearly 299,792 km/second, usually rounded to 300,000 km/s, or 186,000 miles/s to the same digital accuracy. Once measured, we know that this same value is measured in every non-accelerated *inertial* frame in the Universe.

Maximum speed of a material particle Nothing with mass can travel at c. One must expend an infinite amount of energy to boost a massive particle to light speed. All objects move at speeds below c.

Maximum speed of information transmission Two different inertial frames can exchange information *no quicker* than the time light takes to travel between them.

Lorenz invariance All *SR* physics laws must be universal as defined in the box. Such laws that are applied the same way in all inertial frames are said to be *Lorenz Invariant*.

The *SR* challenge: find the Lorenz invariant form for every law.

> **Physics**: a "law" is an experimentally verified set of rules that control how interactions work out.
>
> A law is *universal* if it can be expressed in exactly the same way in all inertial frames. NP laws are not *universal*, they require special forms for different moving frames.

Simultaneity In any single inertial frame, if two events occur simultaneously, they will never be measured as simultaneous in any frame moving in reference to the "simultaneous" frame.

Causality If two events occur with shorter duration (in an inertial frame) than the shortest interval that a photon can move between them, neither event could have *caused* the other. The earlier could not have been responsible for the later's happening.

Lorentz transformation This is the method used to find the (x, y, z, t) coordinates of a point in a moving frame, given the values in a different one. We describe the best known effects here.

Spatial Extent – *Length contraction* An observer working in an inertial frame will measure the length of an object as shorter than the same measurement made by a moving observer who is at rest with the object.

Temporal Duration – *Time dilation* An observer in an inertial frame will measure the time interval for an event to happen as being longer than the same measurement made by a co-moving observer at rest with that event. One second In the rest frame will appear to have lasted many more seconds to a moving observer. The closer the frame relative speed is to c, the slower its clocks run. Move clocks approach *fully stopped* as the frame speed approaches c.

Relativistic Mechanics All *SR* results can be shown to simplify to their classical NP form when velocities in question are so slow that c may be considered infinite. Here are a few important results —

Mass – In the process of finding Lorentz Invariant laws, the object's rest-frame mass appears to a moving frame as multiplied by the same factor that makes *time* intervals bigger (time dilation). As seen from the ground, a space ship's mass grows to infinity as it speeds up to c.

Rest Frame Mass: This is the mass an object has when measured in the inertial frame where that object does not move. This intrinsic mass is shown as m_0. A photon has no rest frame mass (zero), and moves at light speed.

Total Energy – $E = mc^2$ the total energy of anything measured by an external and moving observer. m is the relativistic mass of the moving system being measured.

Kinetic Energy – $KE = E - m_0c^2$ the difference between an object's total energy and its intrinsic energy, called its rest mass energy. The intrinsic energy due to its rest mass has is the same form as its total energy, but is what would be measured in the *rest frame* of the object where its mass is m_0. For speeds much slower than light, this reduces to the Newtonian kinetic energy, $\frac{1}{2} mv^2$.

Temperature – This is almost always described as the average of the kinetic (motion) energy of all particles in a gas. Actually, it is the average of the $(\frac{1}{2})mv^2$ content of that gas.

Temperature has the Lorentz transformation of a length contraction – the faster something moves, the colder it appears to be.

There is a physics ideology that calls temperature an energy thingy and says that it transforms like energy or mass.

But it is not even *kinetic* energy; something does not become true simply because someone just insists it is. Truth in physics needs to be verified (tests) and justified (mathematics)

Our result for temperature is from kinetic theory, and was first published in 1917 by early Relativity adopter, Richard C. Tolman (1881-1948).

General Relativity (*GR*) **1915** Albert Einstein (1879-1955)

Top-level summary
- The Strong Equivalence Principle is true for all reference frames
- The *structure of space* refers to the geometric paths that photons travel.

The equivalence between **inertial mass** (that responds to springs) and **gravitational mass** (that responds to the mass of nearby objects) is one of the features of the Newtonian paradigm. No one has ever seen any acceleration or velocity change difference between these mass types.

Einstein did note a difference between the way acceleration from an *external force* operated as opposed that from a *gravitational field*.

The Equivalence Principle
Inertial mass is the same as gravitational mass.
Any system will show exactly the same response If its acceleration is due to an external force or to a gravitational field,

Strong Equivalence Principle All physical behavior is the same when under acceleration by an external local force or by gravity.

When you stand on an elevator, the uniform upward force pushes against your feet. Your body muscles transmit the upwards force and keep you from collapsing. If you collapse at high accelerations, your lower body surfaces will still be driven upwards, pushing the rest of you along with them. *Yuck* – with enough force, one could turn into mush. Certainly, if a living object was aboard the prototype of the old U.S. sprint missile when launched at 400 g acceleration, within a fraction of a millisecond it would have been converted into that mush puddle.

When one is accelerated by a uniform gravitational field, every particle of mass in your body feels the same force, no collapse, no *mush alarm*.

Einstein realized that the gravitational response is just like accelerating the entire frame of reference your body resides in – and the classical Equivalence Principle in our box cannot be not quite right. He concluded that inertia reacts to the gravity effects on the space you inhabit not to the force felt by each of your separate particles.

He expanded *SR* with the ***Strong*** Equivalence Principle and all its implications. If gravity actually modified space, then space is no longer a linear thing, it must bend and warp, in response to local mass concentrations and how they are moving. *Bending* and *warping* apply to the collection of all light paths, not any structure in the aether.

Inertial mass $m = E/c^2$ The meaning "Inertial Frame" changed from the viewpoint of a non-accelerated location to to one of a neighborhood about a local mass. Everywhere, the inertial mass that responds to a force is the total energy divided by the square of the light speed.

Photon inertia The energy of light is related to its wavelength and, by the Strong Equivalence Principle, it must have inertia.

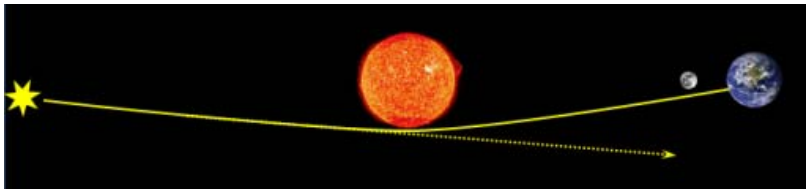

Fig 4 Photon Inertia causes light to bend in gravity

Fig 4 A gravitational field will bend its path just as the Earths field affects an artillery round.

This prediction was first tested in **1918** when a star position was seen to shift in the sky when it passed behind the sun's edge during a solar eclipse. Astronomers refer to this bending of the light path when discussing "gravitational lensing."

Gravitational Red Shift, Gravitational Time Dilation Any frequency shift seen from an accelerating object will be seen as light moves from strong gravitational field to a weaker one.

Fig 5 Light frequency slower (shifted toward red) at surface of sun than at the surface of the Earth. For the sun, this is a wavelength change of parts per million, but has been measured.

Fig 5 Gravitational Redshift. Time runs slower at the bottom of a gravity well.

Clocks tick slower deep in a gravity field, causing light to shift toward the red. This is different from the Hubble red shift of far away objects. The Hubble rate is due to the expansion of space which increases separations between objects, it is not the rate (velocity) that 2 objects move through space.

Warping of Space While developing *GR* , Einstein taught himself the math for the warping of 4 coordinates (3 for space plus 1 for time) required describe the effects of gravity. The photon inertia just mentioned was one result. Here are others.

Frame Dragging Warping of space by a massive object was actually first seen when it explained differences from NP expectations concerning precession of Mercury's orbit.

Fig 6 But, if a mass spins, it must drag space with it, partially due to time duration effects. As seen in Earth orbit, space twists into a spiral close to rotating object (a small effect, but has been measured).

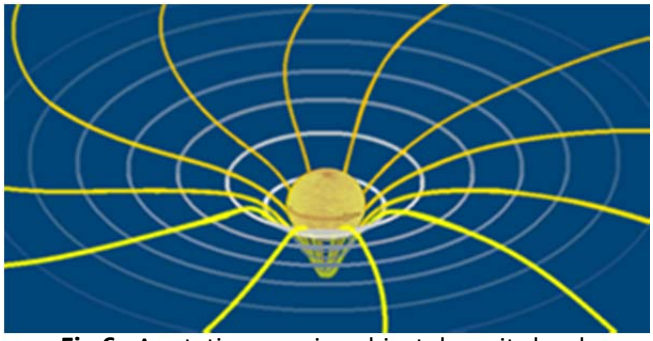

Fig 6: A rotating massive object drags its local space, forcing light paths to twirl about with it.

Expansion of space and the *Big Rip*

Recent data indicate that the Hubble expansion rate is increasing for all the space that makes up our universe. *Objects in space do not expand, it is space itself that expands*. It is the *acceleration* of the expansion that puts a stretching force on all matter that resides in it.

Fig 7 If the stretching of space is high enough, molecular bonds would break, electrons would be pulled from every nucleus, neutrons and protons would stretch apart until even the Strong force is overcome. *Rip!* Proposed reason –an unidentified property called Dark Energy. *GR* theory has a term that might or might not be our culprit; either way, *GR* certainly serves as a test bed to evaluate all proposals.

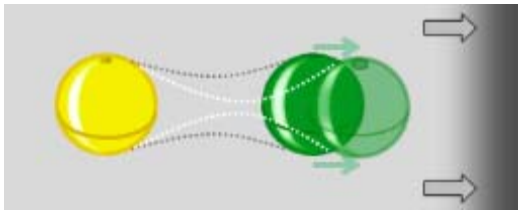

Fig 7: Accelerated expansion of space generates a force that pulls objects apart

Appendix 3 – Quantum Paradigm

The conceptual basis for quantum mechanics, whose success is discussed in our main section.

Quantum mechanics (*QM*) is applied to physical systems much smaller than perceivable by humans, such as atoms, nucleons, electrons, and smaller. We have no words to adequately visualize reality in that realm.

We must use that which we have. Disclosure: truly adequate descriptions use mathematical words, not every-day nouns – the statements sound difficult. We discuss things with as many everyday analogs that as possible, but we have to use the new quantum words. We must use a bit of algebra, too (as little as possible).

After being kicked about by highly-accurate quantum calculations, human understanding has been dragged against its will – and frequently screaming – into *QM* concepts.

- *Anyone who is not shocked by quantum theory has not understood it*. – Niels Bohr
- *It is safe to say that nobody understands quantum mechanics*. – Richard Feynman
- *If you are not completely confused by quantum mechanics, you do not understand it*. – John Wheeler

Tracing the rough path that we have followed to reach today's understanding might be the best way to discuss the quantum paradigm.

A *quantum* of something – The smallest size allowed by nature.
Plural - *quanta*

Old Quantum Mechanics

1901 *Action* **Max Planck** (1858-1947) published the explanation for light being emitted by a "black body," an object whose parts are in complete thermal equilibrium (such as the interior of a perfect oven). Predictions about a black body's emitted energy vs is wavelength was first done in 1893, was pretty accurate for long wavelengths but was horribly wrong for short ones. Planck struggled with ideas until he found something that matched the data.

Action – A physics property with a "feel" similar to energy or momentum.

Action has units of angular momentum, $m^2 \cdot kg/s$ (meters^2 · kilograms / second).

A process is determined (*physics*) when you successfully minimize its total *action*, which is its momentum integrated over the length of its path.

h is about $\frac{6.6}{10{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000} \frac{m^2\ kg}{sec}$

Planck's constant, h The hardest implications were that energy was not emitted or absorbed smoothly, but in discrete bundles that was its frequency times a mysterious constant with units of *Action*. Nowadays, h is best viewed as the basic quantum of *Action*. Its value is very close to 6.6×10^{-34} $m^2 \cdot kg/s$, a very tiny value with historic implications.

Action arose from the powerful 19th century synthesis of NP techniques, and is usually not presented until senior level courses of physics because the calculations use calculus.

Action is like energy – it started as a clever way to rearrange Newton's equations, and –like *energy*– morphed beyond *clever*, into a physically important property, with a conceptual meaning of its own.

Too bad about that unfamiliarity thing – all of quantum mechanics is centered about Planck's Constant, the fundamental quantum of *Action*.

The only way Max Planck could derive his result was via Boltzmann's statistical mechanics – in his time, not universally well regarded because it used probability. And that implied that the objects could not described as classically deterministic, only as unreal *chance*. If the derivation was meaningful, goodbye to our Clockwork Universe. *Unreality*? *Probability*? There just had to be a better way!

Planck called his results a math tool that got correct results, not a new reality. *Mathematical convenience*? But there is no "correct" classical calculation for blackbody radiation. Instead, Max Planck's ideas became the foundation to all of quantum mechanics.

1905 *Wave-particle Duality* **Albert Einstein** (1879-1955) published his explanation of the **photoelectric** (**PE**) effect, 2 years after its experimental discovery had led to unsettling confusion.

Light, considered a wave in the classical NP paradigm, strikes a metal surface as though it were made up of tiny particles. He used the Planck description as though it were exactly true, and proposed the dual nature of reality – light was made up of particles called **photons**, each with energy given by is wavelength (equivalent to frequency),.

Most physicists of the day ignored the idea but Einstein's predictions explained the data too well to be a mistake. He received his Nobel Prize for this work, not Relativity.

PE effect Planck showed the energy of light is

$$E = hc/\text{wavelength}$$

Einstein argued that since it has no rest mass, its momentum must be E/c, so that

$$\text{momentum} = h/\text{wavelength}$$

When light is absorbed by a metal surface, its momentum is transferred the electrons near the surface. If the electron's new total energy exceeds the metal's work function (the material's energy used to hold electrons inside it) it will fly off the surface into space.

1911 *Coulomb Orbit Model*

Ernest Rutherford's (1871-1937) tested the then-popular idea that an atom was like raisin bread, with the *raisin* electrons mixed throughout the positive charged substrate, the *bread*. He fired alpha particles (helium nuclei) at metal foil (collection of atoms) and found extreme back reflection which could only happen if the positive charge was localized to an ultra small core at the center. Rutherford proposed that the negative electrons must be in electrostatic orbits about the positive nucleus.

This answered the experimental issue, but raised a new one – How could *planetary* electrons be stable about a *solar* nucleus? Charges radiate when forced to move in circles and a Rutherford atom must radiate, quickly loose energy, and collapse.

1913 *Atoms – Electrons orbiting a nucleus are* WAVES. **The Bohr Model**

Niels Bohr (1885-1962) applied the successful wave-particle duality of light to electrons in their Rutherford orbit about the nucleus.

Bohr Atom Assumes the Planck-then-Einstein wave/particle duality type of quantization

$$\text{wavelength} = h/\text{momentum}$$

Bohr assumed that the electron's wave nature would mean that its orbit could be wave-stabilized if its wave pattern contained only complete wavelengths around the orbit path: 1, 2, 3, etc. Otherwise, wave overlap would make the wave pattern unstable. He ***postulated*** that the stable wave train did not radiate its energy away and fall into the nucleus as required by classical theory. Discrete stepping of allowed wavelengths meant momentum (and energy) are not continuous in the planetary orbits. The electron's energy must change by discrete steps if it is to change from one stable state to another. His model accurately explained observed patterns in the emission of light from hydrogen gas.

Fig 8 is a Bohr model with 12 complete wavelengths. The net path is the dotted classical orbit that the particle part of the electron follows.

This is the mechanism for a quantum orbit – an electron's wave train wraps about its orbit like a circular parade of elephants, each holding the tail of the one in front of it – there must be a countable number of complete elephants (wavelengths) around the orbit with the end of one being the start of the next.

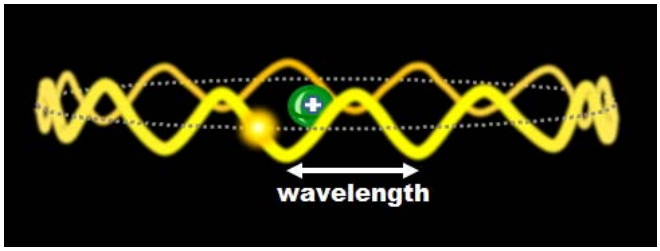

Fig 8: Bohr's model for hydrogen. The electron's particle nature follows the classical orbit, its wave nature requires integer number of wavelengths, 12 are shown here.

Quantum Steps The wavelength count in a stable atom is always an integer. So an atom that starts with n=4 (4 wavelengths fit around the orbit) and changes to n=3 (the wavelength expands and now only 3 fit along the path), will have lost energy in this shift from one stable state to the next.

Bohr quantization rule An electron in orbit about the nucleus obeys

momentum *times* wavelength = nh

Physicists may have hated the model but they could not ignore it. For a shift of n=4 to n=3, the predicted lost energy corresponded to one of the discrete light wavelengths actually seen emitted by neutral hydrogen!

Bohr knew that his quantization rule was the *Action* variable calculated along the orbit path, *Action* = nh. As his theory developed, he discovered several different quantum numbers similar to n, all of which give meaning to the observed finer details of the hydrogen spectrum. He knew that circular orbits were approximations for the actual elliptical ones (like a comet orbiting the sun).

1916 *Relativistic corrections.* **Arthur Sommerfeld** (1869-1951) realized that an electron particle would be subject to relativistic mass change as it moved along its elliptical orbit between perigee and apogee. He applied special relativity mechanics to the model with spectacular results: new quantum numbers popped up. Each changed by integers; each produced predictions that faithfully reproduced spectroscopic data.

But there were some features of the hydrogen atom that even Sommerfeld's work could not duplicate. In retrospect, the model used causally deterministic rules; he should have incorporated probability into the *Action* calculations.

Deterministic vs. probabilistic imagery. Fig 9 A-C show different ways to image the famous Halley's Comet which orbits the sun every 75 years.

Fig 9A 1910 Photo of Halley's comet taken from Earth. The cometary core is on the left

Fig 9B 1986 Halley photographed from orbit, by spacecraft *Giotto*

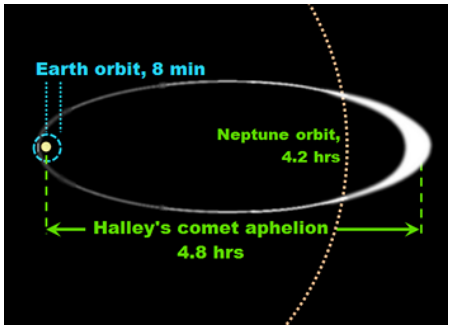

Fig 9C The orbit as a probability plot, distances are shown as the time for light to go between the sun to the object.

Fig 9A is how Earth people saw comets throughout recorded history. **9B** is the cometary nucleus seen by a space probe. **9C** is how you must describe Halley's location at random times during a million year interval. Halley spends more than half of its time in the outer neighborhood of Neptune, only a year within Earth's orbit, and the white is proportional to its being in that point. The comet example is only a weak analogy to atomic structure.

(1) An electron in the Bohr model orbits much faster than the time for the atom to interact with atom and about a million times faster than chemical reactions. If Sommerfeld had tried to develop a statistical probability distribution, would he have been led to mature quantum theory before Heisenberg and Schroedinger?

(2) The Bohr model never succeeded with 2 electron helium. Physics does not handle 2 masses that *for example* are tied to the ceiling by springs and to each other by a third spring. The resulting motion is chaotic – non-deterministic, it can not be predicted. It is no surprise that models with multiple interacting electrons failed. Statistical projections are the best predictions we can make for our example of 2 masses coupled by springs.

This ends our discussion of the Old *QM* Paradigm with its cause-and-effect orbits that allow us to visualize what is happening. Modern *QM* is not deterministic – it generates probability descriptions that duplicate lab data with extreme precision. Probability is hard to picture in one's mind, which is why **Fig 3A** is most useful for precise calculations to understand data, but **Fig 3B** is our tool to visualize electrons bound to the nucleus.

Modern Quantum Mechanics

de Broglie waves. *All* particles of matter always have associated quantum waves

$$\text{wavelength} = \text{h/momentum}$$

1924 *Matter Waves* Louis de Broglie (1892-1987) followed up on Bohr's result postulating that **ALL** pieces of matter have associated waves. This was also highly controversial. But within 3 years, Davisson and Germer at Bell Labs observed wave diffraction from a beam of electrons. This meant that when electron particles moved through narrow slits, they behaved exactly like waves of water or light. This was startling validation of the **wave-particle duality**. . By the end of the decade, tests showed that even beams of hard atoms will diffract. Conclusion – de Broglie waves *must* be part of our Reality.

1925 *Matrix Mechanics* Werner Heisenberg (1901-1976) published the first true *QM* calculations for the intensity (brightness) of light emission from hydrogen. Waves had no part in his work, Heisenberg was to say that below a certain size level, there was no reality, just mathematics.

Max Born (1882-1970) quickly showed that Heisenberg's method is best summarized using the methods of matrix algebra. The Heisenberg/Born method was became labeled *matrix mechanics*.

1925 *Wave Mechanics* Erwin Schroedinger (*German*- Schrödinger, 1887-1961) followed de Broglie's lead, developed his wave equation and published calculations for the hydrogen atom. The oscillating "thing" was called the wave function and Schroedinger described it as determining the probability of properties of the atom. Any technique using the Schroedinger Equation was called *wave mechanics*.

1926 *QM Equivalence* Schroedinger showed that Wave Mechanics and Matrix Mechanics were different ways to perform the exactly same calculation for quantum systems.

At this time, Born developed the key property of *QM*, now called Born's Rule, which showed that the probability for the realization of an event (such as for a particle registering *here at this point* on a measurement screen) is the (complex) square of the amplitude of the (complex) wave function. Born received the Nobel prize in 1954 for this achievement.

1926-1930 *Copenhagen Interpretation* Heisenberg, Born and Jordan developed a set of *QM* interpretations and rules that were presented at several meetings and finally published in Heisenberg's 1930 book, The Physical Principals of Quantum Theory.

1927 *Uncertainty Principle*

Heisenberg proved that the assumption that both the exact position and exact velocity of a particle can not be precisely known (become realized) at the same instant.

The Uncertainty Principle is a direct consequence of the *QM* mix of waves and probability. The *uncertainty intervals* we call Δ are the root mean square deviation from the calculated expectation value, called the **standard deviation** in normal statistics.

Uncertainty Principle. Refers to parameters that generate the ***Action*** parameter, such as location and velocity. Both can be calculated with precision, but the value realized ("measured") for both can only be predicted as being *near* the calculation, within some interval around them; $\mathbf{\Delta_x}$ for position and $\mathbf{\Delta_p}$ for momentum = mv.

QM says there is always a *minimum uncertainty*, $\hbar$ ("h bar") in the knowledge about conjugate pairs. $\Delta_x \cdot \Delta_p \geq \hbar$

Note: $\hbar$ indicates the Planck constant divided by 2π, $\hbar = 1.1\times10^{-34}$. If the two Δ uncertainties are same size, both would be $\Delta \geq 10^{-17}$ in their own units of measure.

My own introduction to this was through Heisenberg's classical example of an optical microscope which follows much the same relationship (without the $\hbar$). It is not a *Strange! Mysterious!* quantum-jump thing, it is a result of the wave nature of the probability that underlies our universe.

Heisenberg's Uncertainty Principle is a very strong statement. For example, if you know the actual position of an electron (or any other quantum particle) exactly, then at that same instant, you are not allowed to have *any idea at all* as to how fast it is moving! Strange as this principle seems, it is fundamental to the entire spectrum of *QM* thinking. Minimum uncertainty is pretty small, about 1/100 of the diameter of the hydrogen nucleus (also known as the charge diameter of the proton).

We, in our macro-scale world of classical physics, are never aware of the fundamental uncertainty that applies to everything. My pen is 15 cm from my hand, and seems to be laying quietly. But Planck's constant is so tiny-small that I really cannot specify its location to a fraction of any particular atom, a size that would be under the influence of the Uncertainty Principle. I can not even say that my pen is truly still because I do not know whether or not it experiences even the tiny thermal jitter that would be a million million times larger than uncertainty limit. This fundamental limit in the quantum realm does not impact my direct awareness in any way.

1927 *Complementarity* Niels Bohr extended the wave-particle duality principle to describe the interaction between the quantum probabilistic reality and the classical world we experience.

> Niels Bohr,1949, Discussions with Einstein on Epistemological Problems in Atomic Physics:
> *"however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms*. The argument is simply that by the word "experiment" we refer to a situation where we can tell others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics."

In other places he spoke of the classically incompatible visualization of oscillating matter waves and chunks of matter (particles) speeding about on their own trajectories. He was concerned about "lab" results using totally different methods with results that seemed to be valid but contradictory. He strongly urged that both should be accepted as *complementary* views.

To me, this has an anthropomorphic ring to it that seems to echo medieval concepts of man being the center of the universe and focus of all Creation. But Niels Bohr apparently saw it as the resolution to incompatible worldviews. In his later years, Bohr tried to expand complementarity outside of quantum world. He apparently said that in *any range* of activity, any two conflicting things should be considered as complementary.

Personal view I believe that Bohr was using our personal experiences to highlight that:

> *Throughout the universe things must happen through steps that can be consistently explained.*
> *The universe must develop through processes that do not depend on the specific involvement of sentience.*
>
> Reality is the web of interconnected probability whose waves and associated mass interact with macroscale objective matter. Such interactions cause the wave-like probability and particle-like potentials to converge (physics: *collapse*) into fully realized events. The new events and their associated objects continue the interactions that generate the new convergences. Such events could be the diffraction of electrons or the collision of objects with mass (i.e., momentum). Both are complementary descriptions of the pre-collapse state.

The newly converged "events" could be the laboratory diffraction of neutral atoms (seen before 1930), or the magnetic deflection of alpha particles (the tool Rutherford used). Atoms are atoms, and we should not impose non-quantum prejudgments upon the reality of either descriptions.

Quantum Physics 6 —

1927 *Relativistic quantum theory*

Paul Dirac (1908-1984) applied special relativity to the Schroedinger wave equation in a unique way that was able to account for the electron and its quantum spin. We become *mathy* now.

Dirac realized that the wavefunction was actually a vector (called a spinor) in an abstract probability space and he derived 2 equations, one that described the electron and one that posed a problem because it produced unphysical negative energy solutions. Dirac's inspriration was that this second solution was for a new kind of particle that was just like the electron but had negative energy. This was the anti-electron, or *positron* for its postitive charge.

Dirac's effort was not the first application of *SR* to the Schroedinger equation, but was first completely successful one that could apply to electrons with their quantum spin. It also is the first method to show the existance of anti-particles.

The prediction of anti-particles was experimentally verified within a few years, and Dirac's relativistic wave theory became a landmark discovery, ranking right along with the original Heisenberg and Schroedinger non-relativistic quantum theory. This has been successfully generalized well beyond spin 1/2 electrons and forms the key basis for modern quantum mechanical calculations.

Quantum Electrodynamics (***QED***) Dirac then applied his techniques to developed the quantum theory of electromagnetic fields. *QED* became the basis for most extensions of *QM* to sub-atomic particles, which now the Standard Theory.

Renormalization *Problems in paradise* To successfully complete calculations, the physicists had to simplify the equations by expanding them, but the expansions generated infinities (math phrase, *did not converge*).

Renormalization solves the infinites issue and yields answers that are the measured values. The pairing of terms was not strictly valid mathematically; its anti-logic made people nervous. Renormalization has been intensely studied and no longer causes the same anxiety. It is now known that certain theories can be renormalized, and there are some that cannot. For example, General Relativity is a non-renormalizable theory.

Under renormalization, the things that grow to infinity are paired with other independent terms that also go to infinity and cancel. The issue comes up when the expansion is done for different scale lengths – very small, larger, much larger, much much larger, and so on.

Richard Feynman, one of renormalization's creators, called it a "shell game" –a mathematically illegitimate magic trick.

QM and General Relativity don't work together.

SR and *QM* are marvelous together. It was hoped that *GR*, the super correction to *SR*, would do amazing things when mixed with *QM*. But it does not work. It is not because *GR* is a deterministic theory and *QM* is probabilistic, after all, *SR* is as deterministic as classical physics can be and *QM* merged well with *SR*.

Field theory of gravity in *QM* would require massless, spin 2 gravitons to supply the attraction, but the universal attraction of gravity leads to the infinities that renormalization was to handle. Oops, *GR* fields are non-renormalizable and blow up (infinities again) when you examine very small regions.

Many people are hard at work on attractive but different ideas that might lead to the merger and produce the long sought *Theory Of Everything* – but for now, no joy. We are stuck with *QM***'s** micro regime and RP**'s**. macro regime.

Probability leads to weird behaviors. Many of *QM*'s strange, unnatural things (see Appendix 3 **intro**) are due to probabilities. Mixed state behavior is one – classical probability for 2 events is their combination (physics: superposition) in a formula that is exactly like the the *QM* formula. Neutrinos come in 3 types that can change into each other. For a long enough path, a neutrino beam will reach an equilibrium mixture where the 3 populations appear in a standard proportion. This is the **Markov effect** in classical statistics. What about the mysterious entanglement? 2 opposite states, A and B, can become entangled into a superposition until at least one become realized – at which point if A occurs here, B must be present there. We will discuss this in a later post. For now, it is safe to say that almost no one understands all there is about probability.