Lecture given at the ***Science and New Technology Special Interest Group***
at ***The California Club,*** Los Angeles, California, USA
October 17, 2006

Layperson's Description of
High-Frequency Gravitational Waves or "HFGWs"

By Robert M. L. Baker, Jr.

It is Recommended to the Non-scientist, Engineer or Mathematician that they Scroll Down to the Appendix of this Tutorial for a more Detailed and Simplified Discussion of the Detection of High-Frequency Gravitational Waves in the Four-Dimensional Spacetime Continuum

What are high-frequency gravitational waves or HFGWs? Visualize the luffing of a sail as a sailboat comes about or tacks. The waves in the sail's fabric are similar in many ways to gravitational waves, but instead of sailcloth fabric, gravitational waves move through a "fabric" of space. Einstein called this fabric the "space-time continuum" in his 1915 theoretical work known as General Relativity (or GR). Although his theory is very sophisticated, the concept is relatively simple. This fabric is four-dimensional: it has the three usual dimensions of space: (1) east-west, (2) north-south, (3) up-down, plus the dimension of (4) time. Here is an example: we define a location on this "fabric" as 5th Street and Third Avenue on the forth floor at 9 AM. We can't see this "fabric" just as we can't see the wind, sound, or gravity for that matter. Nevertheless, those elements are real, and so is this "fabric." If we could generate ripples in this space-time fabric, then many applications become available to us. Much like radio waves can be used to transmit information through space, we could use gravitational waves to perform analogous functions. Still the question arises … how can we generate and detect these gravitational waves in the space-time fabric? One way we can generate wind waves is by the motion of fan blades. Likewise, gravitational waves (GWs) can theoretically be generated by the motion of masses. We can detect wind waves by the motion of a weather vane. Similarly, we could detect gravitational waves by a transient change in a dimension, such as the distance between two points at the ends of a ruler. Gravitational waves will make the ruler seem to behave, to an outsider observer, as if it was made of rubber, stretching and contracting. However, the change in length would be extremely small, smaller than the diameter of a proton! Ordinarily we would not be able to observe it, but scientists are now testing techniques to detect gravitational waves by very accurately measuring the distance between two points (technically it is called the Laser Interferometer Gravitational Observatory or LIGO), which went into operation about two years ago. So, Gravitational Waves are like other waves, but they exist in a rather strange fabric of space-time.

Now comes the tough part: how are gravitational waves generated in nature? One possible generation mechanism is a double-star orbit, two stars that circle around or orbit each other. If these stars are very heavy, perhaps black holes, then there exists an incredibly large **change** in force, called centrifugal force, as they orbit one another. According to Einstein's publication in 1916 (a year after his GR) such a rapid change in force over a brief time generates gravitational waves and he developed an equation – the "quadrupole" – to estimate the gravitational-wave power from a source, such as orbiting stars in 1918. At the time it was believed by the scientific community that these "gravitational waves" were just artifacts of Einstein's theory and probably didn't exist in a meaningful form. Then two astronomers – Hulse (a student) and his professor Taylor were studying a radio star pair at the huge Arecibo radio observatory in Puerto Rico (it's 305 meters across). The star pair they observed was coalescing and the energy it was loosing during this coalescence was **exactly** as predicted by Einstein. They received the Nobel Prize in 1993 and from then on the skepticism evaporated and all scientists believed that, due to this indirect evidence, gravitational waves did indeed exist. However, the gravitational waves generated by these star pairs are of very low frequency, only a few cycles to a fraction of a cycle per second. So if the stars orbit very tightly around each other with a period of, say, one second (for comparison, the period of our motion around the Sun is one year), then the gravitational-wave frequency is two cycles per second or two "Hertz," (2 Hz for short – gravitational waves have twice the orbital frequency according to Einstein's theory). If black holes spun around each other during the final phase of their coalescence (or "death spiral") in say one fortieth of a second, then their frequency would be 80 Hz. For a reference, US house current has a frequency of 60 cycles per second (60 Hz) whereas radio waves have frequencies of thousands or millions of Hz. These Low-Frequency Gravitational Waves (LFGWs), generated by changes in force (for example, during the orbiting of two black holes), could be detected by LIGO if they exhibited frequencies from 40Hz to 2000 Hz. And there are high-frequency gravitational waves (HFGWs) still reverberating around the universe generated by the Big Bang and our Earth is bathed in the sea of these relic GWs. But what use are these gravitational waves if we can't harness their potential? To be useful we not only need to detect them… we need to generate them. So, could gravitational waves be generated in the laboratory? It's obvious we cannot have two black holes orbiting in a laboratory, but it turns out we really don't need to. The trick is that we **don't require gravitational force** to generate gravitational waves! It's really the motion of the mass that counts, not the kind of force that produces that motion. How do we obtain a large force change? To make it practical we need a force that is much larger than the force of gravitational attraction. Let's do a thought experiment and think of two horseshoe magnets facing each other (North poles facing South poles). They will attract each other strongly. If we reverse the magnets, put them down back-to-back with their poles facing outwards, then primarily their gravitational force acts due to their masses and we sense little or no attractive pull. As a matter-of-fact, magnetic, electrical, nuclear and other non-gravitational forces are about 1,000,000,000,000,000,000,000,000,000,000,000,000 times larger than the gravitational force! So, if we have our choice, we want to use "electromagnetic force" as our force, not weak little gravity.

How could we make use of this analysis and generate GWs in the laboratory? Instead of the change in "centrifugal force" of the two orbiting black holes, let us replace that force change with a change of non-gravitational force, the much more powerful one of electromagnetism. One way to do this is to strike two laser targets with two oppositely directed laser pulses (a laser pulse is an electromagnetic wave). The two targets could be a small masses, possibly highly polished tungsten. Each laser-pulse strike imparts a force on the target mass acting over a very brief time, commonly defined as a "jerk" or a shake or an impulse. Einstein says, according to his broad concept of "quadrupole formalism," that each time a mass undergoes a change or buildup in force over a very brief time; gravitational waves are generated – **in the laboratory!** The duration of these pulses is very short—a very small fraction, perhaps only one thousand billionth of a second, but that short duration leads to an extremely high frequency, on the order of billions cycles per second (say, 1,000,000,000,000 Hz or a Terahertz or THz) for this pulse duration. And such high GW frequencies of over 100,000 Hz have been defined by Stephen Hawking as HFGWs. The combination of two masses in the form of laser targets acted upon (jerked) by two lasers is one embodiment of a laboratory HFGW generator. Another embodiment of the concept is to replace the laser targets by two clusters of millions of very inexpensive little piezoelectric crystals found in cell phones and energized by thousands of inexpensive Magnetrons found in microwave ovens. The little crystals each produce a small force change, but millions or billions of them operating in concert produce a huge force change and generate HFGWs. Other ideas could involve molecular-size resonators or even off-axis spinning atomic nuclei. These HFGWs that will soon be generated in the laboratory have wonderful and revolutionary applications that low frequency gravitational waves simply do not have!

But what are those wonderful applications of HFGWs? The successful completion of the experiment in China, Russia, the US, or anywhere else, to prove that HFGWs can be generated and detected in the laboratory would be even more important than Marconi's development of the Radio Telegraph. Besides almost assuring a Nobel Prize for whoever successfully accomplishes the HFGW generation/detection experiment, there would be tremendously lucrative commercial and military applications. Some examples:

(1) Multi-channel communications (both point to point, for example to deeply submerged submarines, and point to multipoint – like cell phones-- through all ordinary material things – the ultimate wireless system). One could communicate directly through the Earth from New York in the United States to Beijing in China, without the need for fiber optic cables, microwave relays, or satellite transponders – antennas, cables, and phone lines would be things of the past! Even the timing afforded by HFGW stations around the globe could result in at least a **50 Billion dollar** savings in conventional telecom systems over ten years according to a recent analysis of Harper and Stephenson. Essentially it would allow for greater telecommunications bandwidth usage efficiencies by synchronizing, through the use of HFGWs (which, unlike electromagnetic waves, move at constant speed through the Earth and atmosphere) all telecom transmitters and receivers. Thus no communication time would be needed for "waiting" for messages to appear – one message could follow right after another since you know precisely (to nanoseconds or better) when they will come in. Specifically, Harper and Stephenson find cost savings in communications message search-space and frequency-reference improvement and phase-noise reduction. Each savings is small, but their analyses show that Billions of dollars in telecommunications costs could be saved.

(2) As discussed in the authoritative text by Landau and Lifshitz, HFGWs provide a remote means for causing perturbations to the motion of objects such as missiles (anything from bullets to ICBMs), spacecraft, rogue comets or minor planets that are destined to impact Earth, land or water vehicles or craft – **a totally new propulsion system!**

(3) Remote coalescing of clouds of hazardous vapors, radioactive dust, etc. by changing the gravitational field in their vicinity.

(4) The potential for through-earth, or through-water "X-rays" utilizing the extreme sensitivity of HFGW generation-detection systems to polarization angle changes (possibly less than 10^{-40} radians or one Billion, Billion, Billion, Billionth of a degree) in order to observe subterranean structures, geological formations (such as oil deposits), create a transparent ocean, view three-dimensional building interiors, buried devices, hidden missiles, weapons of mass destruction, achieve remote acoustical surveillance or eavesdropping, etc. – a full-body scan without radiation danger.

(5) the potential for remotely disrupting the gravitational field in a specific region of space (using a HFGW "beam") and even producing nuclear reactions there – possibly without any radioactive waste!

(6) Possible dermatological applications since Dr. Lawrence Moy has determined that HFGWs might tighten facial muscles and reverse the aging process!

If Einstein's quadrupole formalism holds, and we expect it does as I wrote in a recent Journal ***Astronomische Nachrichten / Astronomical Notes*** peer-reviewed scientific paper, then GW radiators (e.g., laser targets, clusters of piezoelectric crystals, off-axis spinning nuclei, etc.) could be placed at lunar distance. By adjusting them a remote GW focus, which would itself be a powerful, movable, remote HFGW emitter could be moved to any point above, on, or under the Earth's surface – certainly a fantastic possibility! There are no commercial or military secrets here since all of the technology is openly disclosed in the four patents now issued (2006) in the United States and China (6160336, 6417597, 6784591 and 100055882.2) and the 16 pending in the U.S., Europe, Russia, and China. By the way, low-frequency gravitational waves do not have any of the foregoing applications. The next question that arises is what steps would need to take place, once minute amounts of HFGWs are generated and detected in the laboratory, in order to eventually realize the fantastic possibilities of HFGWs? The first experimental laboratory model could be enlarged many fold and still remain within practical funding limits. For example, 200 lasers (rather than two utilized for one possible HFGW generation experimental apparatus) could be positioned at a distance apart some one-hundred-times larger than the experimental version (say, tens or hundreds of kilometers apart). Hundreds of billions of piezoelectric crystals and hundreds of millions of microwave-oven Magnetrons could be positioned in clusters many kilometers apart – even extending to the Moon's distance. According to published theory, and assuming that the quadrupole formalism holds at least approximately at these distances, this would increase HFGW power some 100,000,000 fold!

(1) Using such an enhanced HFGW generator, HFGW receivers (detectors) could be positioned on the opposite side of the globe to test through-earth communications.

(2) First sensitive accelerometers, then massive objects, say 50 kilograms, could be tested for gravitational-field change and movement at the HFGW generator's focus.

(3) Various aerosols could be tested for coalescence at the focus.

(4) The HFGW detectors on the opposite side of the Earth from the generator could be moved around over known geological formations to determine if the characteristics of the GWs change (especially an extremely small polarization angle change) depending upon intervening material. In fact, detectors local to the

HFGW generator could be utilized to determine the effect of particular objects and materials placed between the detector and the more powerful HFGW generator.

(5) Even with the less powerful experimental HFGW generator the gravitational-wave intensities could be many times larger than the intensity of sunlight at the Earth's surface! Strong disruptive events (including nuclear) could result in very small regions of space at the focus and generation of energy is a possibility without hazardous nuclear waste.

Actually though, such a question of technology transfer is difficult to answer. The same question put to Marconi, after his successful test of miniscule radio-telephone power, would not have revealed the revolutionary applications of his experiment to microwave ovens, cell phones, radar, television, etc. The same will no doubt be true of the applications of a successful HFGW-generator test.

What is actually going on now (2006)? Let's examine and discuss the current Chinese initiatives in the area of HFGW generation, detection and applications. In October 2004 the Chinese invited me to carry out a month-long lecture tour of Chinese universities and institutes. They had an active program in HFGW research – as opposed to the US where I was unable to obtain either interest by the US scientific establishment or funding for HFGW research. The Chinese have an HFGW project funded by various Chinese Foundations. I had formed a team of US scientists interested in HFGW (GRAVWAVE® LLC) and accomplishing some unfunded research (the team includes Professor Clive Woods, the Department Chairman of Electrical and Computer Engineering at Louisiana State University, Dr. Buzz Aldrin, the Astronaut, Dr. Eric Davis, a Senior Scientist at The Institute for Advanced Studies at Austin., and a few others). Next year we may participate in the Chinese HFGW Project and be funded by them. But why is there no US interest? `

For the answer let me go back to when Hulse and Taylor received the Nobel Prize in 1993 for their indirect confirmation of the existence of gravitational waves. Prior to that time there had been some effort to detect gravitational waves – specifically, by Dr. Joseph Webber who, along with his protégé in the project, Dr. Robert Forward, fabricated a meter-sized Aluminum bar at the Hughes Research Facility in Malibu, California called the "Weber Bar." The idea was that the bar would resonate or "ring" when gravitational waves passed by. After a year or so of operation the device did not detect any gravitational waves; but Dr. Forward believed that it eventually would. In 1960 I invited Dr. Forward to present a lecture on gravitational waves to my staff at the Lockheed Astrodynamic Research Center in Bel Air, California and that was when I first became interested in gravitational waves. Weber's device never made a detection, but after the 1993 Noble Prize the skepticism over gravitational waves evaporated. Scientists from

Caltech (including Professor Kip Thorne) and MIT sought funds from the National Science Foundation to construct the Laser Interferometer Gravitational Observatory (LIGO). They initially asked for about 390 million and by the time it went operational its price tag rose to over half a billion dollars. Like the Weber Bar there has not yet to been a detection, but it could come at any time. Now the group is soliciting in excess of 200 million for an "Advanced LIGO" and then a space-based Laser Interferometer Space Antenna or LISA, which may cost as much or more than the current LIGO. This is a long way around to explain why the US scientific establishment does not want to fund High-Frequency Gravitational Wave research – it would be an unwanted diversion from its Low-Frequency Gravitational Wave detector aspirations and hundreds of scientists worldwide are on the "LIGO payroll." Unfortunately, at the lower frequencies and longer wave lengths (thousands to millions of meters in wavelength) there do not exist any of the potential practical applications already discussed. Then there is the inherent reluctance of top scientists to look into something new especially if they, or their immediate colleagues, have not themselves discovered the novel concept. The old "Not invented here" complex. The famous scientist Dr. George Chaplain put it best in an E-mail he sent to me when he heard of the Chinese interest in my work:

Re: Gravitational-Wave Research — Page 1 of 2

Robert M. L. Baker, Jr. Ph. D.

From: George Chapline [chapline1@llnl.gov]
Sent: Tuesday, August 17, 2004 12:48 PM
To: robert.baker.jr@comcast.net
Subject: Re: Gravitational-Wave Research

Dear Bob,

I'm very pleased to hear that someone is interested in funding your research on HFGW; I've always thought this was worth pursuing. As you probably well know both DARPA and NSF are part of "old boys" networks. Unless you personally are a close friend with someone there - forget it. Just be thankful that the Chinese are not as close minded on the subject of HFGW as the U S funding establishment.

george chapline

DARPA = Defense Advanced Research Projects Agency (the research and development agency for the US Department of Defense)

NSF = National Science Foundation Dr. Chapline is the senior physicist at the Lawrence Livermore National Laboratory, USA. He was Edward Teller's Principal Assistant. Teller developed the Hydrogen Bomb.)

We are, nevertheless, driven by both scientific curiosity and the prospect of manifest potential practical applications to accomplish the HFGW test. Several technical papers found at www.Gravwave.com provide the interested scientist or technical person a more complete and technically detailed analysis of HFGWs, their generation and detection in the laboratory experiment. As I said in a lecture I delivered in Europe in 2002 at the *Max Planck Institute* in Munich:

The time is right, *carpe diem*... seize the moment! And on with the experiment!

APPENDIX

Economic Round Table, The California Club
Robert M L Baker, Jr., January 28, 2010

CAN I EXPLAIN IT?

Albert Einstein once said "It should be possible to explain the laws of Physics to a barmaid." Well, as much fun as that might be, I think I better start with you folks.

There are many ways to explain or understand something. Let us consider gravity itself. Most of us don't need an explanation, we are ***comfortable*** with the idea that we all "stick to the floor." Like Einstein himself we wonder a little about when we ride in an elevator and stick to its floor a little more when we are going up than when we are going down, but we don't worry about it much. The fact that 2 + 2 = 4 and not 3 or 5 also doesn't concern us much since we are used to this trivial outcome of number theory. We "know" that ten years is a decade and that a century is 100 years and that a thousand thousand is a million. We do not worry that 60 seconds makes a minute and 60 minutes makes an hour or that there are 360 degrees is a full circle, We are, again, comfortable with these concepts and need no explanation. We also don't need to have an explanation why a triangle has three sides – well it is simply by definition isn't it? So why then would we need an explanation of a detector of high-frequency gravitational waves in the fabric of four-dimensional spacetime? Raise your hand if you would understand such a device and be able to explain it to another. You are not alone since there is probably no one, even Einstein in his day, who really understands such a device or even the high-frequency gravitational waves in the fabric of spacetime that it measures! I might ask the same question at the end of this tutorial. Again you probably won't raise your hand – but, hopefully, you will hesitate a little and, equipped with the figures I will now distribute, be able to explain a little about the measuring device to a friend. Right now, of course, we are mystified by such a device and not ***comfortable*** with it and we could not now explain it to friend.

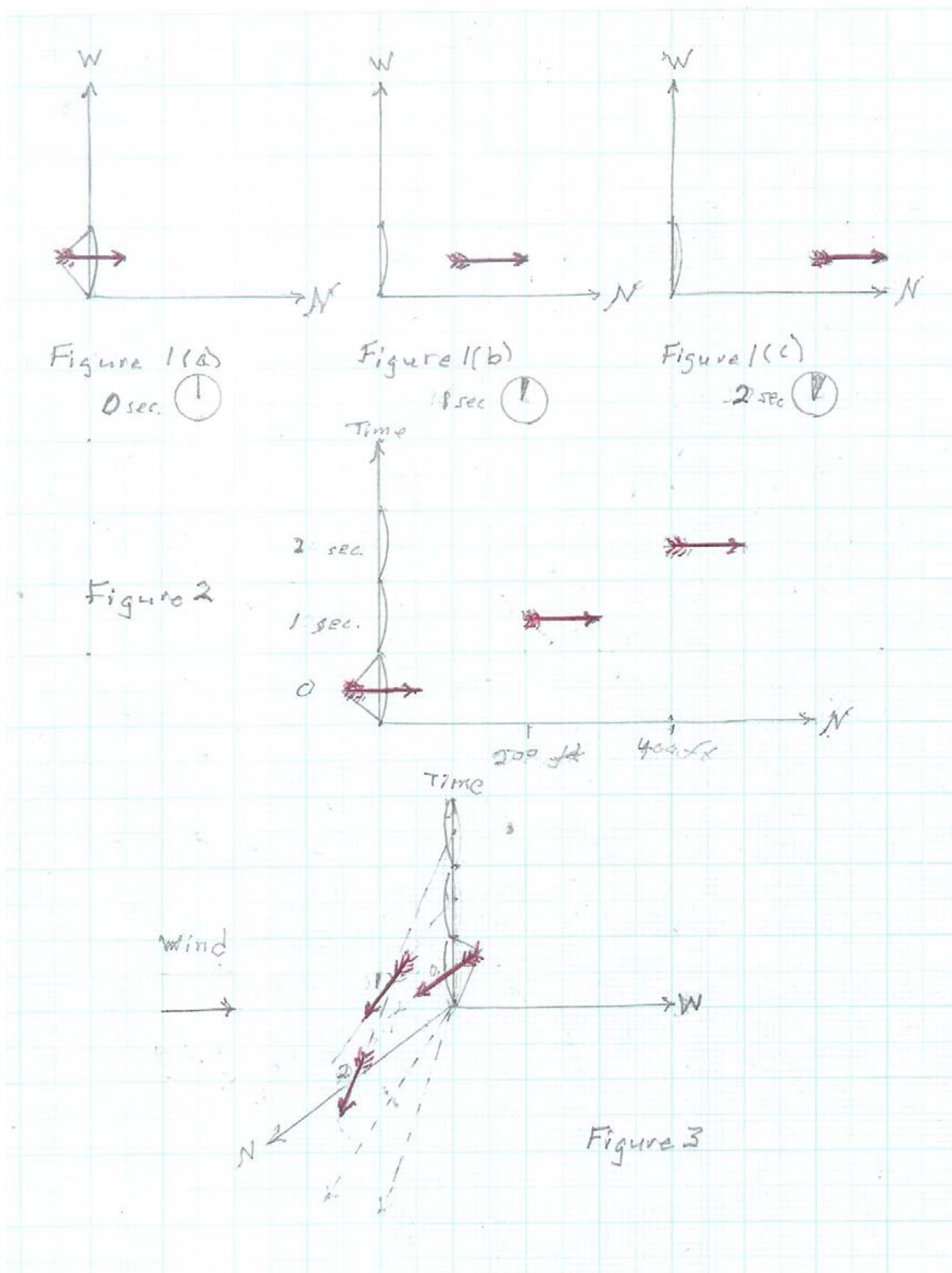
At the outset I must warn you that I will be dealing with the confluence of two extremely vexing and mystifying concepts: waves and spacetime. Like teaching new concepts in the classroom, the best way is to take it step by step. The smaller the steps the better!

OK; let's first all consider what a wave is. Probably you think that the concept of a wave is neither vexing nor mysterious. We are comfortable with the concept of an ocean wave, a ripple or a wave in a flag or sail and probably with a sound wave and possibly even comfortable with a radio wave and a microwave. Wait a minute here – we are talking about two distinct kinds of waves. Water waves and waves in flags or sails are moving in some perceptible medium – liquid and fabric – sound waves, light waves and microwaves are moving in something we can't see. We are comfortable with a sound wave because we sense it with our ears and someone has told us (or even displayed it on an oscilloscope) that it is a "sound wave." Likewise for a light wave that we sense with our eyes or with a microwave that we sense when we touch a resulting cup of hot coffee. But their medium, that is something else. OK sound goes through the medium of invisible air – on the other hand light, microwaves and radio waves go through the empty void of outer space – no medium at all! One of the hardest things to accept in modern physics is that waves can propagate **without** a medium. On the other hand how can we visualize a wave without a medium? The answer is that we cannot. A medium is simply an idea or mental aid to help us be comfortable with the concept of a wave.

But, aside from the absence of a medium, what exactly is a wave? Simply speaking a wave is a moving “bump” that exhibits a height (called “amplitude”), a length (called “wavelength”) and, if there are a series of such bumps, then how often they occur (called “frequency”). For a typical ocean wave its amplitude is measured in feet (about three feet or more for an ocean wave near shore) and the crests of such waves can be as little ten to over one hundred feet apart (their wavelength) and their frequency might be 10 seconds between their crashing on shore. Frequency is usually measured in terms of how many occurrences per second. So in this case it would be about one-tenth of an occurrence per second or a tenth of a “cycle” per second. The meaning of the term “cycle” is the rate of occurrences per second or, in this case, one-tenth of an occurrence per second or one-tenth of a cycle. As we will see later, “low-frequency” gravitational waves can be generated by orbiting masses and if the time it takes for them to get around each other is measured in seconds, for example ten seconds, then the frequency of the gravitational waves they generate could be on the order of one-tenth of a cycle per second.

The term “high-frequency wave” is established “by definition” just like we define a triangle as a figure having three connected straight lines -- it has three sides. The definition of high frequency for gravitational waves was given in a book coauthored by the famous Theoretical Physicist Stephen Hawking. In this case the term pertains to waves having frequencies greater than 100,000 cycles per second. A thousand cycles per second is defined as a “kilocycle” so one would say that the frequency of high-frequency gravitational waves is greater than one-hundred kilocycles. Actually the frequency of gravitational waves created during the beginning of our Universe (the “Big Bang”) could have frequencies measured in “gigacycles’ where a gigacycle is defined as a billion cycles per second. As an aside, the frequency of the microwaves in a conventional microwave oven is about two and one half gigacycles. In this case microwave crests impinge on your coffee cup in such an oven two and one-half billion times a second and the molecules in the coffee in the cup are so shaken up that the coffee heats up.

But let’s get back to “spacetime.” Here we have our second vexing and mysterious concept. It is very important to realize that for most if not all of us we are entering uncharted territory. We are three-dimensional creatures. Like waves without a medium we cannot visualize things in more than our three dimensions. But let’s try anyway. The easiest way to explain spacetime is by considering simple examples. In our case let’s consider archery, a bow and arrow. In the plan view of Figure 1a we see the bow drawn back and aimed in the North direction (the West direction is off to the left of the archer). After one second the situation is as shown in Figure 1b and after two seconds as is shown in Figure 1c. OK so far so good.

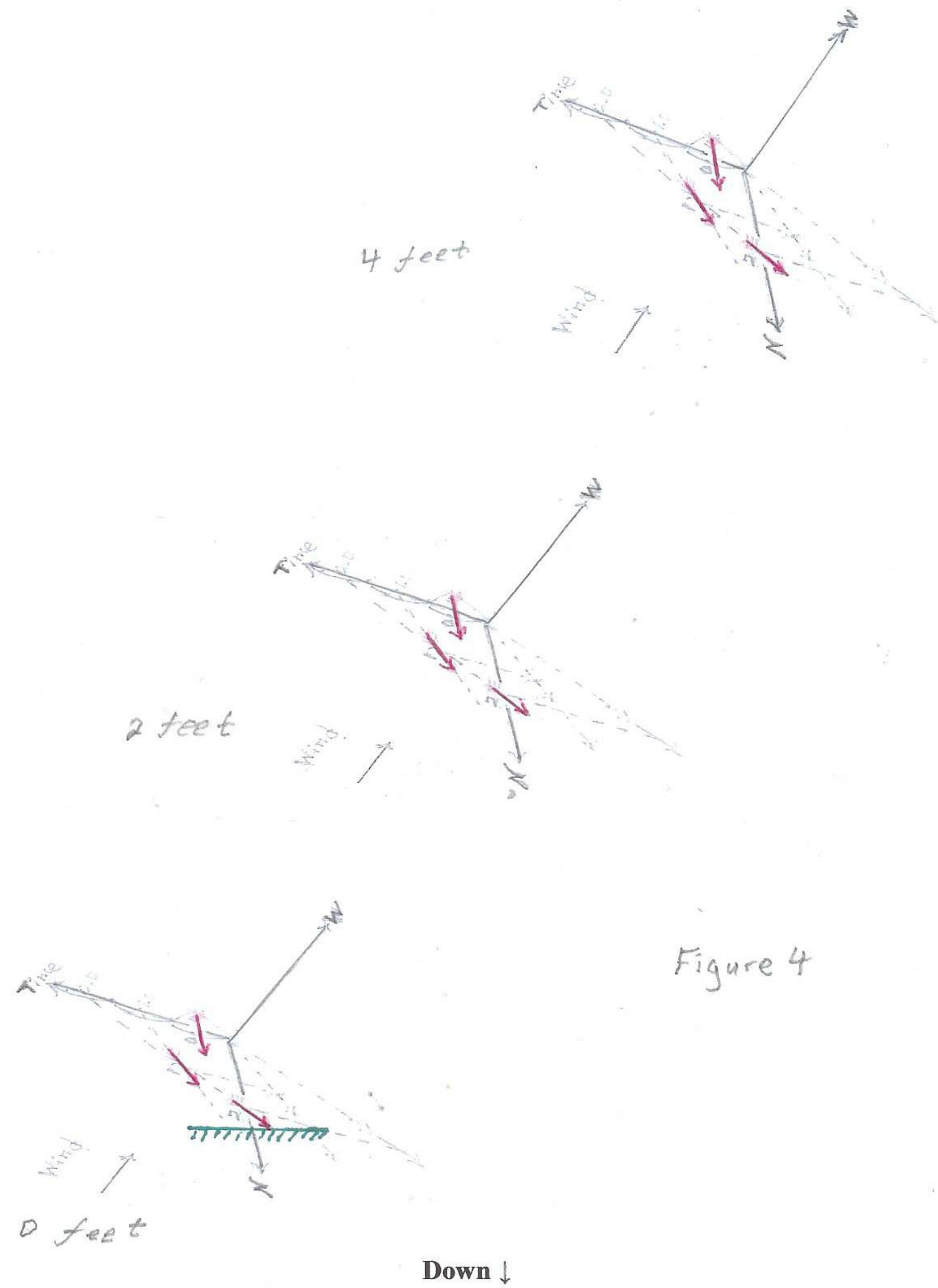


Let us now get to the "dimension" of time. Considering time as a dimension may be new to many of us – so let's go a little slow. We next stack the a, b and c of

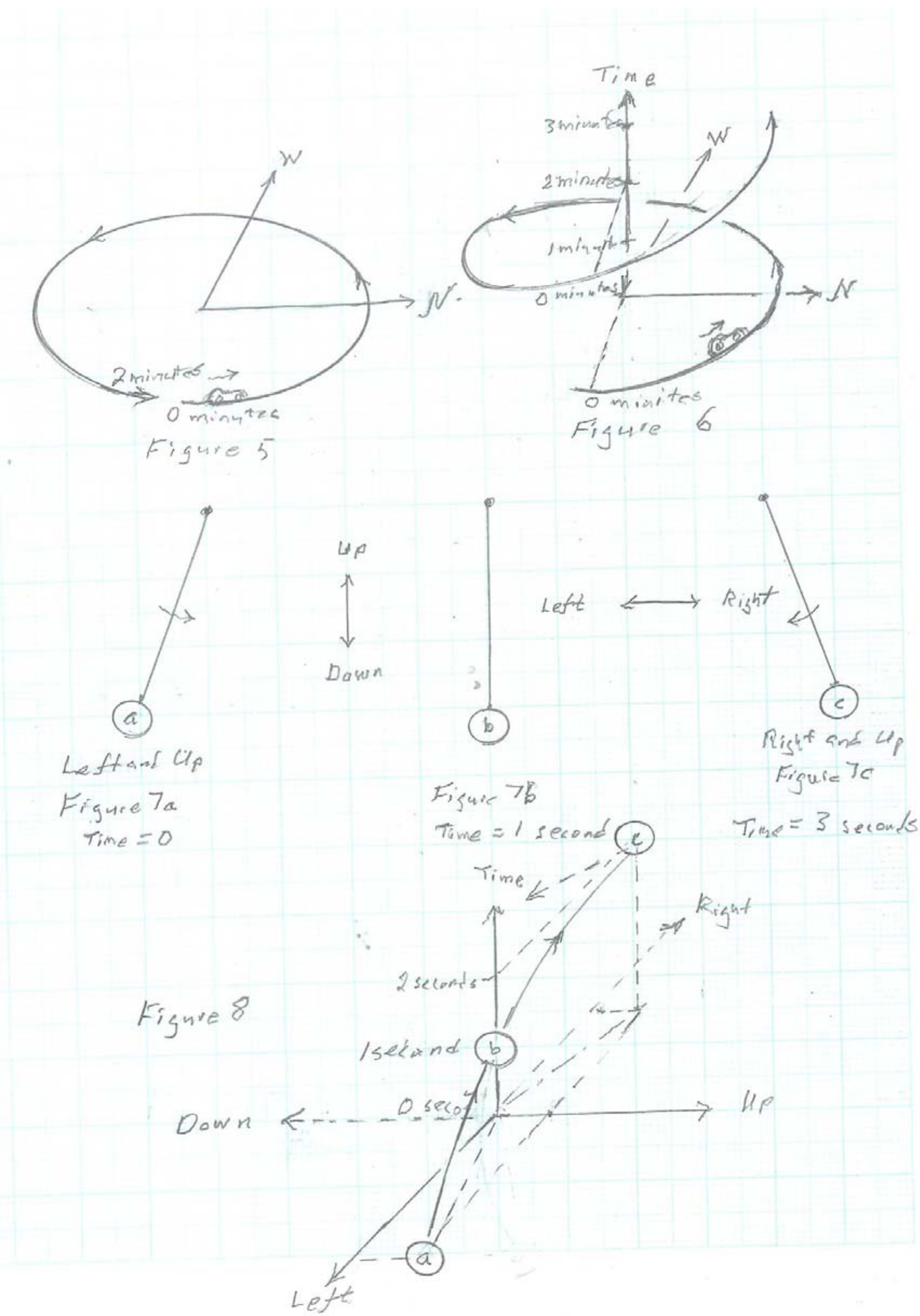
Figure 1 on top of each other as in Figure 2. The West direction of Figure 1 has been replaced by the Time "direction" in Figure 2 (0 to 2 seconds). This "direction" is the Time "dimension." There are some analogies here. We are probably all familiar with the heart-beat oscilloscope display of a patient's heart beat in a hospital setting … then suddenly the graph goes flat ("flat liner") and the patient dies – in this rather morbid analogy the time dimension is along where the wiggly heart line goes (usually to the right) while the patient is still alive.

So far we have worked in two dimensions only: North-West in Figure 1 and North-Time in Figure 2. Now let's go to three dimensions. We assume that a wind is blowing out of the East sending the flight-path of the arrow off to the West. The situation is shown in Figure 3 in which the Time direction is drawn perpendicular to the North and West directions. I hope that everybody understands these three dimensions. We understand them because we can draw them even on a two-dimensional piece of paper, BUT four dimensions is going to be very difficult to visualize in fact almost impossible!

One way to visualize four dimensions is to think of taking the flat portrayal of three dimensions of Figure 3 and simply replicating it on a paper as in Figure 4. In this case we have added the third space dimension up-**Down.** Essentially, like all real arrows, if it doesn't hit something like a target, then the arrow falls "down" to the ground (shown in green at the bottom of the figure) dropping from four feet to two feet to zero (hitting the ground). There you have it, but still difficult to visualize I'll bet. It's like a strange creature called a "flat worm." Its whole "Universe" has only two dimensions of space. When confronted with a three-dimensional barrier it is confused and stops.



It may help clarify the matter to look at a second example. This time let's consider a sports car going around a circular track as exhibited in Figure 5 in which we show the North and West directions or dimensions. It takes the sports car about two minutes to get around the track Again we will take the vertical axis to be Time. In Figure 6 we see that in North, West and Time dimensions, the sports car follows a spiral or helical path in spacetime. But where is the forth dimension: Up-Down? In this case the forth dimension is in the sports car itself! Whenever the driver adjusts his seat up or down he utilizes motion in the forth dimension. Can you visualize it? Possibly not, so let's consider yet another example. We take the motion of a pendulum as in Figure 7 in dimensions left-right and up-down. Figure 7a is the pendulum at time zero, Figure 7b at 1 second and Figure 7c shows the pendulum at 2 seconds. Figure 8 shows the movement of the pendulum bob during this time interval in the three dimensions of Left-right, Up-down and Time. Note that at a the bob is Left and Up, but at time level 0. At b the bob is neither left nor right nor Up or Down – it is at zero space coordinates but at a time level of 1 second and at c it is Right and Up and at time level 2 seconds. Again the question is: where is the forth dimension? Well this is a trick question because a pendulum's motion can be completely defined in only the three dimensions shown in Figure 8. That is its path is totally defined in two space dimensions , left-right and up-down, and time. A pendulum is a perfect device for a flat worm!


W
N
2minutes
0 minutes
Figure 5
Time
3minutes
2minutes
1minute
0 minutes
W
N
0 minites
Figure 6
Up
Down
Left
Right
a
b
c
Left and Up
Figure 7a
Time = 0
Figure 7b
Time = 1 second
Right and Up
Figure 7c
Time = 3 seconds
c
Time
Right
2 seconds
Figure 8
1second
b
0 second
Down
Up
a
Left

Unlike the flat worm, however, we humans have the capacity to imagine things and that is the key to understanding both waves and spacetime. Visualize the luffing of a sail as a sailboat comes about or tacks – the cloth is two dimensional with waves or ripples in a third dimension with motion perpendicular to the face of the sailcloth. The waves in the sail's fabric are similar in many ways to gravitational waves, but instead of sailcloth fabric, gravitational waves move through a fictional, yet mind-pleasing, "fabric" of space. Einstein called this fabric the "space-time continuum" in his 1916 work known as General Relativity. Although his theory is very sophisticated, the concept is relatively simple. As we have discussed this fabric is four-dimensional: it has the three usual dimensions of space—for example, east-west, north-south, and up-down—plus the fourth dimension of time – like in Figures 4 and 6. However it is important to recognize that space and time are not tangible "things" in the same way that water, woven sailcloth and air are. It is really incorrect to think of them as a 'medium' at all. No physicist or astronomer versed in these issues considers spacetime to be a truly physical medium; however that is the way in which our minds prefer to conceptualize this idea of spacetime. This "fabric" is exactly what is sketched in Figures 4 and 6. It is difficult to think of these sketches as representing a fabric, but this mind-satisfying fiction describes exactly what they do – move in a four-dimensional "fabric." As I have said before, we can't "see" this "fabric," just as we can't see wind, sound, or gravity for that matter. Nevertheless, those elements are real, and so is this "fabric." If we could generate ripples in this space-time fabric, then many valuable applications would become available to us. For example, much like radio waves can be used to transmit information through space, we could use gravitational waves to transmit information right through the Earth itself!

So let's summarize what we have learned, but under the proviso that we really use our imaginations. When asked what was more important than knowledge, Einstein replied that imagination was since knowledge has limitations, but imagination is unlimited. To drive this point home, I will digress with two imaginative ideas conceived by famous scientists to help visualize a concept: "Maxwell's Demon" and "Schrödinger's Cat."

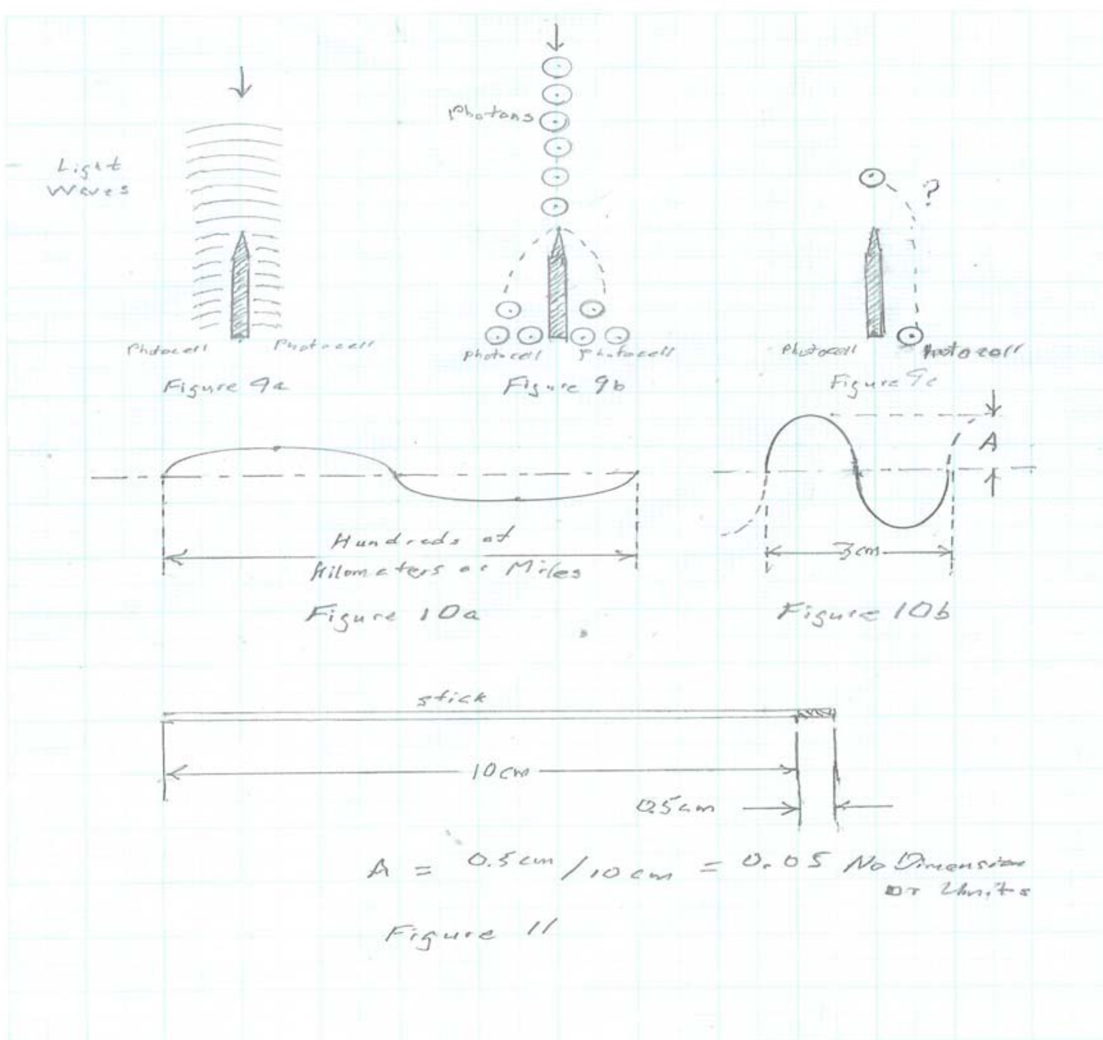
Maxwell's demon is a thought experiment, first formulated in 1867 by the Scottish physicist James Clerk Maxwell, intended by Maxwell primarily to "show that the 2nd Law of Thermodynamics has only a statistical certainty," and commonly used for imagining the possibility of violating the second law. The concept was named by Lord Kelvin. The second law of thermodynamics states that the disorder of an isolated system, termed "entropy," which is not in equilibrium, will tend to increase over time, approaching a maximum value at equilibrium. This law ensures that two bodies of different temperature, when brought into contact with each other and isolated from the rest of the Universe, will evolve to a thermodynamic equilibrium in which both bodies have the same temperature. This seems like common sense, but in Physics sometimes common sense is wrong. Any way, suppose that you have a box filled with a gas at some temperature. This means that the average speed of the molecules is a certain amount depending on the temperature. Hot molecules go fast and cold molecules go slow. Some of the molecules will be going faster than average and some will be going slower than average. Suppose that a partition is placed across the middle of the box separating the two sides into left and right. Both sides of the box are now filled with the gas at the same average temperature. Maxwell imagined a molecule sized trap door in the partition with his minuscule creature, the demon, poised at the door who is observing the molecules. When a faster than average molecule approaches the door he makes certain that it ends up on the left side (by opening the tiny door if it's coming from the right) and when a slower than average molecule approaches the door he makes sure that it ends up on the right side. So after these operations he ends up with a box in which all the faster than average gas molecules are in the left side and all the slower than average ones are in the right side. So the box is hot on the left and cold on the right. Then one can use this separation of temperature to run a heat engine by allowing the heat to flow from the hot side to the cold side. Well it sounds like perpetual motion. And how does the demon operate? For instance where does the energy for it to open and close the trap door come from and how does he sense the speed of the molecules and how is he instructed what to do? And you thought visualizing four dimensions was difficult and a real stretch!

Schrödinger's Cat is also a thought experiment, often described as a paradox, devised by Austrian physicist Erwin Schrödinger in 1935. It illustrates what he saw as the problem of an interpretation of quantum mechanics applied to everyday objects. (As technical background, one could read: *Nature* Volume **454**, pages 8-9, 2008, published online 2 July 2008, **"**Reincarnation can save Schrödinger's cat**.")** This is a hypothetical experiment in which we put a cat inside a box with some equipment which releases poisonous gas on detection of electrons that may enter the box at random and have a 50:50 chance of entering the box in one hour. In this case, after an hour, one would say that he doesn't know whether the cat is dead or alive, and this can be known only by looking inside the box. But according to quantum theory, it is better to say the cat is half dead or half alive, until we check on it. Confused! Look at it this way, we have no idea at all whether or not an electron has entered the box, set off the poison and killed the cat. But if each of us would bet, since the odds are even half of us would bet that the cat is alive and half that it is dead. Not so with quantum mechanics – here we must assume that the cat is half alive and half dead and that with a large number of boxes (and cats) half would be alive and half dead. With standard microscopic quantum mechanics it is required that macroscopic objects, such as cats, do not always have unique classical descriptions. The purpose of the thought experiment is to illustrate this apparent paradox. Our intuition says that nothing can be in a mixture of states; yet the cat, it seems from the thought experiment, can be such a mixture. Is the cat required to be an observer, or does its existence in a single well-defined classical state (dead or alive) and require another external observer? Each alternative seemed absurd to Albert Einstein, who was impressed by the ability of the thought experiment to highlight these issues. In a letter to Schrödinger dated 1950, he wrote and I paraphrase:

"You are the only contemporary physicist, besides who sees that one cannot get around the assumption of reality, if only one is honest. Most of them simply do not see what sort of risky game they are playing with reality—reality as something independent of what is experimentally established. Their interpretation is, however, refuted most elegantly by your system of radioactive atom + electron + amplifier + poison gas + cat in a box, in which the system contains **both** the cat alive and dead. Nobody really doubts that the presence or absence of the cat is something independent of the act of observation."

Confused? Yes, and I look at the concept or paradox a little differently. A beam of light is focused directly at a knife edge as in Figure 9a. If we place photocells on each side of the knife edge, then each will detect exactly half of the light waves impinging on the knife edge. But in the quantum theory of light we do not have waves, but a series of photons hitting the knife edge as shown in Figure 9b.

Again the photocells will detect exactly half of the photons impinging on the knife edge. But lets suppose that there is only **one** photon impinging on the knife edge as in Figure 9c. It cannot be split and must either go to the right side or the left side of it. But while heading toward the knife edge was there something intrinsic in the photon that made it a "right going" or "left-going" photon? No there is nothing "in" the photon that tells it that it is even going toward a knife edge! So "how do it know?" That is the question and the paradox of quantum mechanics! That is what Schrödinger's Cat is all about; before opening the box how do you know the cat is either dead or alive? You don't.



This reminds me of a well-known story – perhaps you have heard it before. Several people are seated around a campfire speculating on the greatest invention of all mankind. One says "It's the steam engine – started the industrial revolution" another says "The radio – lead to all modern communication" another said "the Airplane – lead to all modern travel' another exclaimed "Nuclear Energy!" Then one person spoke up and said "Of course, it must be the Thermos Bottle." "Why the Thermos Bottle?" "Well," he replied, "… in the winter when it's cold and you put hot soup in it, it says warm and in the summer when it's hot and you put cold lemonade in it stays cold. " "So?" another replied. "Well, how do it know?" And how does the observer of the box containing Schrödinger's Cat or of the photon know?

Back to my explanations. So now we need to combine the mysterious concept of "waves without a medium," which I discussed at the outset, with the even more mysterious concept of the fabric of four-dimensional "spacetime." Here we must use another analogy or imagery to visualize a gravitational wave. One of the consequences of the passage of a gravitational wave through the fabric of spacetime is that it actually changes the dimensions of an object; but very, very, very slightly (another consequence is that a high-frequency gravitational wave also can interact with microwaves, but we will discuss that later). It is like a shimmer that we might see in looking at a desert panorama during a hot day – a "heat wave" or perceived periodic changing of an object's shape or size or a "mirage." This effect is the basis for the Laser Interferometer Gravitational Observatory or LIGO. The LIGO instruments consist of kilometer-long evacuated tunnels whose lengths are continuously measured by sensitive interferometers. These interferometers are instruments sensitive to a change in the tunnel's lengths even to a small fraction of the diameter of a proton … and that is really small! Low-frequency gravitational waves (as mentioned previously, exhibiting a fraction of a cycle per second up to a few hundred cycles per second frequency) can be detected by LIGO and exhibit wavelengths that can be hundreds of kilometers or miles long. The source of such low-frequency gravitational waves could be the coalescence of a pair of **black holes** on orbit about one another. There are other detection instruments similar to LIGO in Europe called Virgo and GEO600. But we are interested here in high-frequency gravitational waves having frequencies greater than one hundred kilocycles. We will discuss the sources of such high-frequency waves in a minute, but let's review the description of waves.

First, consider wavelength. In Figure 10a we see a long wavelength of, say hundreds of kilometers or miles. In Figure 10b we see a short wavelength. This drawing is actually to scale and exhibits the gravitational-wave wavelength of high-frequency gravitational waves from the Big Bang or beginning of our Universe. The wavelength here is three centimeters or 1.2 inches and the frequency is about 10 gigahertz or ten billion cycles per second. I also had earlier mentioned the amplitude of a wave. I show it as *A* in Figure 10b. But what is its dimension or units – cm, inches, kilometers or miles? No it has **no** units, it is a ratio of the length of an object, say a ten-centimeter long stick as in Figure 11, to the change in the stick's length due to the passage of a gravitational wave, say half a centimeter. Thus the amplitude equals 0.5/10 = 0.05 or five hundredths.

In 1992 a brilliant Chinese scientist, Dr. Fangyu Li, developed a new theory concerning high-frequency gravitational waves at Chongqing University, called the "Li-Effect." He had accomplished graduate work in Russia at the Gravitational-Wave Department of Moscow State University under the tutelage of

Professor Valentin Rudenko. Rudenko was one of the leaders of the high-frequency gravitational wave research effort in the Soviet Union during the Cold War. Professor Li's theory was quite different from, but built upon the 1962 theory of another Russian scientist and high-frequency gravitational wave pioneer, M. E. Gertsenshtein. Gertsenshtein had discovered that gravitational waves of high frequency could produce electromagnetic waves, such as light, in the presence of a magnetic field. The effect was very weak but theoretically present. Dr. Li found that if one had a beam of electromagnetic radiation, such as microwaves having the same frequency and direction as the high-frequency gravitational waves, and if a magnetic field was applied, then other microwaves would be generated that not only were much stronger than those generated by the Gertsenshtein effect, but went off in a different direction than the direction of the microwave beam and the magnetic field. During the 1990's I studied Dr. Li's theory and applied it to the detection of high-frequency gravitational waves. In 2001 I applied for a Chinese Patent of the instrument and it was granted in 2007. It is now called the "Li-Baker High-Frequency Gravitational-Wave Detector." It is not, however, the first such detector of high-frequency gravitational waves. At Birmingham University, England and at a major Italian laboratory in Genoa such detectors were actually constructed and recently, in 2008, a detector for such high-frequency gravitational waves was built at the National Gravitational Observatory of Japan. None of these detectors, however, are nearly sensitive enough to detect the waves from the Big Bang or for practical global communication use, whereas the Li-Baker Detector is! By the way, Dr. Li's theory has been validated by some eight technical journal articles, peer reviewed by scientists presumably well versed in General Relativity, published since his original article in 1992.

A schematic of the Li-Baker detector is shown in Figure 12. The "Hour-Glass" shaped image in the center labeled "**S**ynchro--resonant EM GB" is the microwave beam exhibiting the same direction and frequency as the high-frequency gravitational wave (HFGW) signal from the Big Bang or from a HFGW communications transmitter. The green disks represent the poles of the magnetic field. The blue plates in the center are actually represent microwave-reflecting "mirrors" that focus the "detection photons" produced according to the Li-effect at two microwave receivers (#1 and #2). Too fast again? Let's slow down. Suppose you are standing up and high-frequency gravitational waves from the sky are directed right down your body from head to toe. Put a microwave transmitter on your head pointed down in the same direction as the high-frequency gravitational waves and also having their frequency. Now extend your arms. Place the South Pole of a magnet in your left hand and the North Pole in your right hand. The magnetic field will go right through your body and cross both the high-frequency gravitational wave beam and the microwave beam in your chest. Due to the Li-Effect detection photons, that is microwaves due to the high-frequency gravitational waves, will come out of your chest and back and be focused at sensitive microwave receivers in front and behind you. OK – you **are** the Li-Baker high-frequency gravitational wave detector now – Congratulations you are now a new eye to the Universe!!

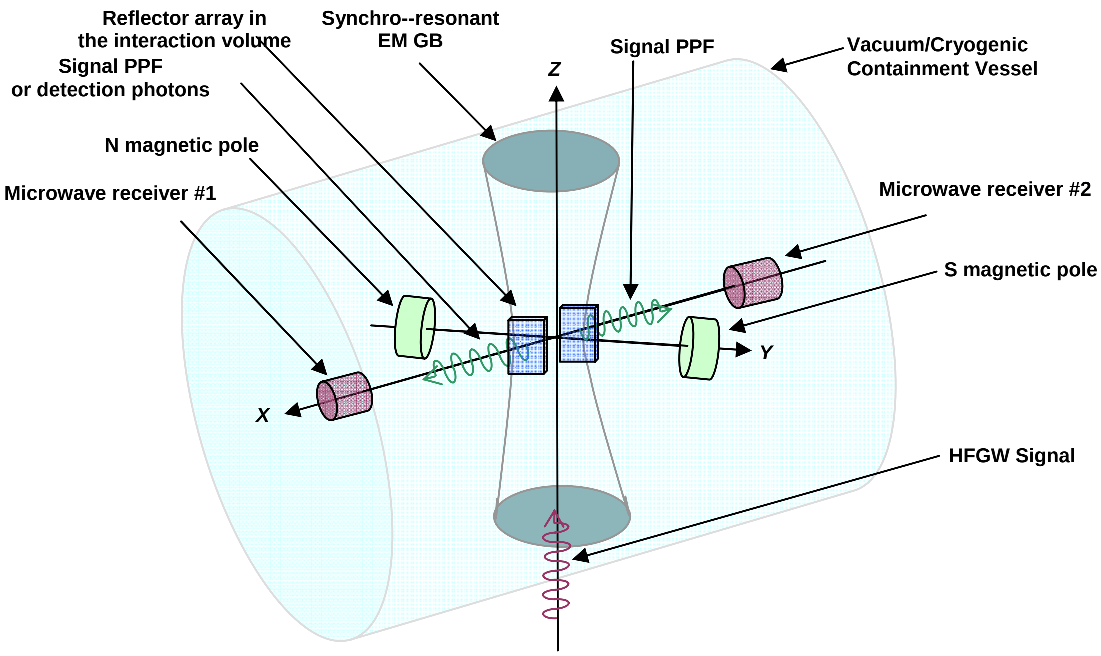


Figure 12

Li-Baker High-Frequency Gravitational Wave Detector

All this is well and good, but how do we know that gravitational waves of any frequency actually exist? As Bob Tranquada remarked in his recent talk here, a "Scientific Theory must be testable to be believed." Since LIGO and other low-frequency gravitational wave detectors and the three existing high-frequency gravitational-wave detectors have not sensed gravitational waves so far, what proof of their existence is there? For that we must take a look at how gravitational waves are generated and again I must call upon your vivid imaginations.

One way we can generate wind waves is by the motion of fan blades. Likewise, gravitational waves (GWs) can theoretically be generated by the motion of masses. As Einstein theorized, two orbiting masses generate gravitational waves. Visualize, if you will, holding two buckets of water, one in each hand, and starting to swing them in a circle and raise them up off the floor. Interestingly enough no water spills out, but seems still to "stick" to the bottom of the buckets. This is an example of what we call "centrifugal force." When the buckets are on the floor gravity holds the water down (the water would float around the cabin of a spacecraft exhibiting "zero g's" or no gravity). When rotated by you, on what amounts to an orbit with you at the center, centrifugal force pushes out and holds the water in place. Now here is where I must call upon your imagination and extreme imagery: the centrifugal force can be represented by what we call a "vector." A vector is like an arrow as shown in Figure 1 that has some direction and magnitude (say the magnitude is the speed of the arrow). Now I want you to work hard to really visualize this arrow at the bottom of each of the orbiting buckets pointed out away from you. OK? In the case of centrifugal force the magnitude of this arrow is not speed but force – say pounds, pushing the water toward the bottom of the buckets and not allowing the water to spill. Now comes the really hard part: the arrow moves as you orbit the water buckets. In fact it assumes different directions as you rotate your arms and the arrowhead traces out a little arc. The tangent to this arc can be represented by another vector. I'll slow down here. The arrowheads trace out a little curved line every fraction of a second during rotation or orbiting. What does this little curved line or arc represent? Well certainly the magnitude of the centrifugal force remains unchanged as long as you keep rotating the buckets at a constant rate, but the direction of the centrifugal-force arrow or vector keeps shifting. This shift represents a CHANGE in the force – not its magnitude but its direction. Once again I call upon your imagination. In Figure 13 is a drawing of the situation. We have a force arrow or vector at one particular time at, say, time zero and other at a later time say time one-hundredths of a second later. There is a little "change" arrow or vector shown at the top of the Figure 13. To be specific we take the magnitude or length of the two centrifugal force vectors to be ten pounds and the little force-change to be one-tenth of a pound. Note that this little change vector is nearly perpendicular to the other two centrifugal force vectors. In our particular example the force change vector is generated over one-hundredth of a second. We establish its magnitude of the force-change vector BY DEFINITION (can't argue with it) as "force per unit time" or in this example 0.1 pound divided 0.001 seconds = 0.1/0.001 or 10 pounds force per second. Finally, I will come to the point: Einstein theorized that gravitational waves are generated by such a force **change**. So it is not the size of the orbiting masses that really counts, but the change in force as they orbit and that force change generates gravitational waves! Whew – a real challenge to understand I know. Perhaps Figure 14 will help.

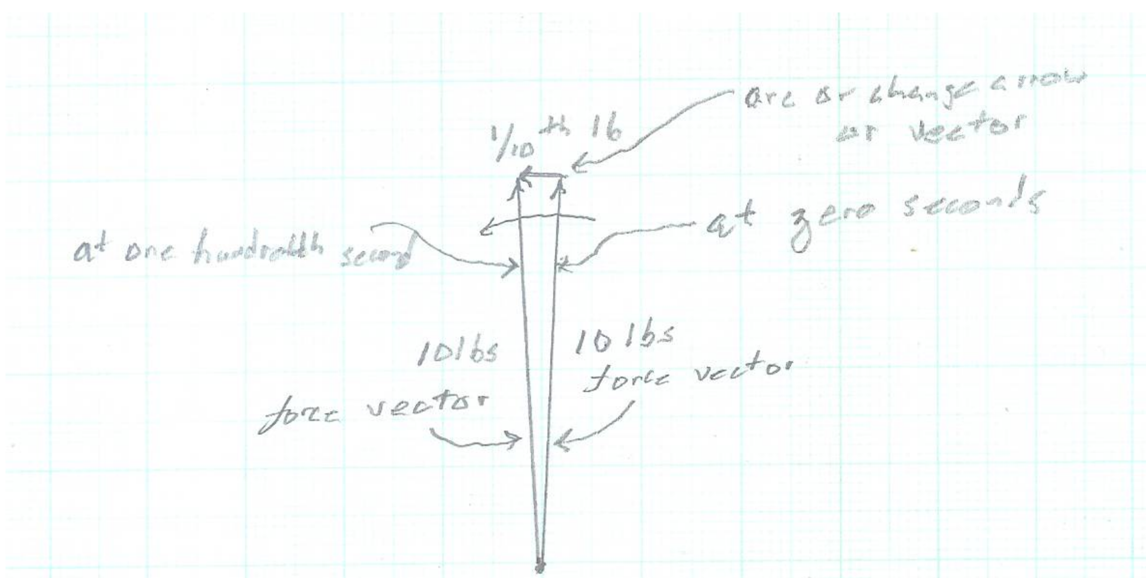


Figure 13

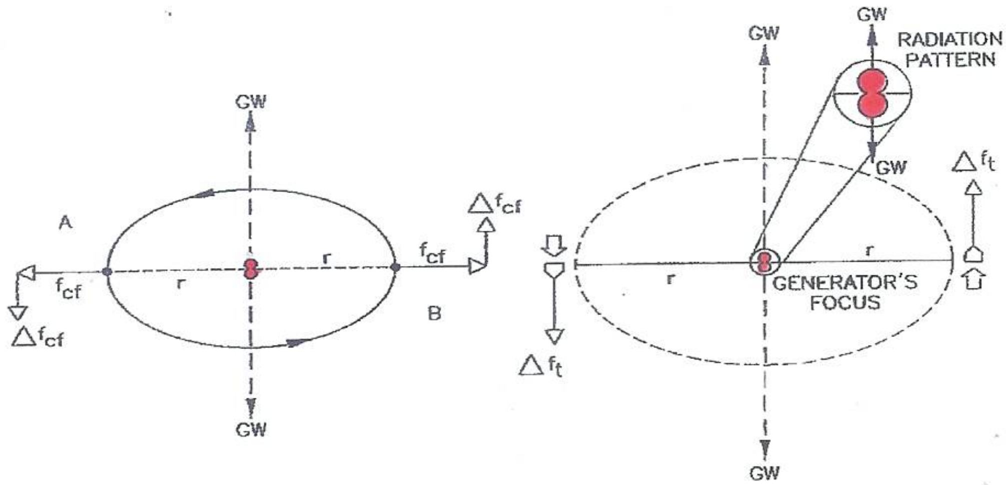


Figure 14

In this figure we find some strange symbols. There is f_{cf} that stands for the centrifugal force vector that we discussed and a Δf_{cf}. This Δf_{cf}. is the symbol for the change in centrifugal force at points A and B on an orbit of two masses. In the middle is a little **red** symbol that is what is known as a radiation pattern, that is a graphical representation of the gravitational-wave (GW) radiation generated by the change in force pairs, Δf_{cf}, that we also have discussed, I will get to the right side of Figure 14 shortly. Besides two masses on orbit around each other gravitational waves can be generated by other activities. During the Big Bang high-frequency ones are generated in a complicated fashion that I won't even try to explain. The mechanism for their generation is like the generation of the cosmic microwave background that was first found accidentally by Arno Penzias and Robert Woodrow Wilson in 1964 as they were experimenting with a supersensitive, 6 meters (20 ft) horn antenna originally built to detect microwaves bounced off echo balloon satellites. When Penzias and Wilson reduced their data they found a low, steady, mysterious noise that persisted in their receiver. This residual noise was 100 times more intense than they had expected, was evenly spread over the sky, and was present day and night (at one point they thought the noise was from pigeon droppings or "the sound from bird shit" as they said at the time). Scientists from Princeton University had reasoned that the Big Bang must have scattered not only the matter that condensed into galaxies, but also must have released a tremendous blast of radiation. With the proper instrumentation, this radiation should be detectable and it was – by accident! Likewise, high-frequency "relic" gravitational waves were theorized by the Russian scientist Leonard Grishchuk in 1975 to be generated during the Big Bang, somewhat before these microwaves appeared.

Now to the experimental evidence of gravitational waves. Two astronomers – Russell Hulse (a student) and his professor Joseph Hooton Taylor were studying a radio star pair (two neutron-star pulsars) at the huge Arecibo radio observatory in Puerto Rico. Hold on! Let's define some new terms here. "Neutron star pair": a neutron star has an incredibly high density – they have a mass of about 1.4 times the mass of our Sun, but are only about ten or twenty kilometers across. This means that a neutron star is so dense that on Earth, one teaspoonful would weigh a billion tons! By pair I mean two on orbit about each other. A "Pulsar" is a rotating neutron star. It is also like a spinning "Lighthouse," whose radio beams sweep around and are seen by our earth-based radio telescopes (like Arecibo). Although the binary companion to the pulsar is usually difficult or impossible to observe visually, the timing of the pulses from the pulsar can be measured with extraordinary accuracy by radio telescopes. Thus it is possible to measure the time it takes the Neutron stars to orbit and to determine if their orbits are coalescing. As I said, they were coalescing and losing energy. This energy must come from somewhere – it was coming from gravitational radiation carrying energy away from the orbiting neutron-star pair! The energy it was loosing during this coalescence was **exactly** as predicted by Einstein due to the radiation of gravitational waves. They received the Nobel Prize in 1993 and from then on the skepticism evaporated and all scientists believed that, due to this indirect evidence, gravitational waves do indeed exist. However, the low-frequency gravitational waves generated by this star pair are miniscule and undetectable, so the LIGO is hoping to detect gravitational waves from more robust sources such as the coalescence of orbiting pairs of **black holes**.

The question arises as to how one could generate gravitational waves in a laboratory setting – certainly a necessity for any practical application of the technology. It's obvious we cannot have two black holes orbiting in a laboratory, but it turns out we really don't need to. The trick is that we **don't require gravitational force** to generate gravitational waves! As we have seen it is really the motion of the mass that counts (their change in force per unit time), not the kind of force that produces that motion. How do we obtain a large force change? To make it practical we need a force that is much larger than the force of gravitational attraction. Let's do a thought experiment and think of two horseshoe magnets facing each other (North poles facing South poles). They will attract each other strongly. If we reverse the magnets, put them down back-to-back with their poles facing outwards, then primarily their gravitational force acts due to their masses and we sense little or no attractive pull. As a matter-of-fact, magnetic, electrical, nuclear and other non-gravitational forces are about

1,000,000,000,000,000,000,000,000,000,000,000,000 times larger than the gravitational force! So, if we have our choice, we want to use "electromagnetic force" as our force, not weak little gravity. How could we make use of this analysis and generate GWs in the laboratory? Instead of the change in "centrifugal force" of the two orbiting black holes, let us replace that force change with a change of non-gravitational force, the much more powerful one of electromagnetism. One way to do this is to strike two laser targets with two oppositely directed laser pulses (a laser pulse is essentially an electromagnetic wave). As depicted on the right side of Figure 14, the two targets could be small masses, possibly highly polished tungsten. Each laser-pulse strike imparts a force on the target mass acting over a very brief time, Δf_t, commonly defined as a "jerk" or a shake or an impulse. Einstein says, according to his broad concept of "quadrupole formalism," that each time a mass undergoes a change or buildup in force over a very brief time; gravitational waves are generated – **in the laboratory!** Other means of generating gravitational waves in the laboratory include crystal oscillators, such as those found in your cell phone, and energizing sub-microscopic particles such as molecules. The Russians, Germans, Italians and Chinese have all proposed such laboratory high-frequency gravitational wave generation means.

Well, I may not have fully explained high-frequency gravitational waves, but I hope that you come away from this tutorial with the realization that scientists rely primarily on imagery to understand and explain things. But so do most of us three-dimensional humans!

Thank you all.