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More on Force

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Every particle ..... reacts in some way to the presence of every other one, although that reaction may be anything from the barest nod of recognition to the explosive violence of annihilation.

– Kenneth Ford

Gravitation: *Celestial bodies exert physical influences on one another*.

The effects of celestial bodies on things terrestrial had been suspected since very ancient times. Effects there sure are, but not of the kind imagined by planetary fortune tellers. Rather, they are related to a magnificent force that reigns supreme in the cosmos at large. This universal force is known as *gravitation*. Its universality was expressed by a poet[1] as follows:

That very law which moulds a tear
And bids it trickle from its source, -
That law preserves the earth a sphere,
And guides the planets in their course.

The law of universal gravitation, especially in its mathematical aspect, was the deep insight of Isaac Newton (1642–1727) though others before him had toyed with similar ideas[2]. The law itself is fairly simple to state: Every mass in the universe attracts every other mass with a force that is directly proportional to the attracting masses and inversely proportional to the square of the distance between them[3]. This simply means that if we double or triple one of the masses the force between them will also be doubled or tripled; whereas if we double or triple the distance between the masses the force of attraction will be diminished to a fourth or a ninth part. It is important to recognize that though the notion of an attractive force was suspected by many before Newton, until its quantitative aspects were formulated, not much could be derived from it, let alone explaining planetary orbits.

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1 Samuel Rogers, *On a Tear*, stanza 6.

2 See in this context, V V Raman, A Background to Gravitattion, *The Physics Teacher*, pp.439–442, November 1972.

3 As a formula one states that the magnitude of gravitational force F of attraction between two masses M_1 and M_2, separated by a distance R is $F = GM_1M_2/R^2$, where G is the universal gravitational constant. Though it was Newton who introduced this, the law of gravitation is not stated in such a form in his classic *Principia*.

Since, unlike the heliocentric model of the universe and the non-astrological framework of astronomy, this law does not contradict any passage in a sacred book, and is silent about the fates and fortunes of people, young or old, religious leaders – the presumed terrestrial defenders of God's words – never objected to its formulation. There was therefore no ugly confrontation with any religious institution, as it happened with Galileo. Political and religious systems where there are no institutional authorities to dictate what is to be believed and what is not, are fortunate in this regard.

Newtonian gravitation has been one of the most successful physical theories. In one grand sweep it accounted for all the Kepler laws of planetary motion, and extended them to the moon and to other satellites, as also to distant stars and planetary systems. Newton himself believed that chemical combinations were also due to gravitational attractions between the atoms of substances, because he used the term to signify any force between bodies After all, this was the only kind of universal force then known. Mellor pointed out[4] that "Newton applied gravitation concepts to atoms, and in this sense he was the founder of molecular as well as of celestial mechanics."

The quantitative aspects of gravitation gave rise to many challenging problems like lunar precession, the three-body problem, the erratic orbit of Uranus, and the motion of mercury's perihelion. These prompted sophisticated analysis and complex calculations. Some of the most creative minds tackled these long before computers were even conceived of, when calculations meant largely hard work and ingenuity. The predictions from gravitation were impressive too: Halley and others could predict the return of their comets, and planets beyond Uranus could be discovered on paper. The applications of the theory of gravitation to celestial motions in the eighteenth and nineteenth centuries constituted some of the greatest achievements of the human mind, seldom recognized, let alone celebrated, in narrations of world history which record in great detail wars and conquests, national rivalries, imperialism, and colonial exploitations.

The theory of gravitation also contributed significantly to the development of mathematical theories and techniques. The grand subject of celestial mechanics arose from efforts to explore and apply the gravitational thesis[5]. Gravitation inspired other domains of physics as well. Priestley and Coulomb derived the laws of electrostatics by suspecting parallels with gravitation.

Today we know that the relevance of gravitation lies primarily at the astronomical level. Gravitation keeps systems stable over long stretches of time. Were it not for gravitation there

[4] J W Mellor, *A Comprehensive Treatise on Inorganic and Theoretical Chemistry*, London, John Wiley and Sons, p.292, 1972.

[5] It was in this context that the theory of potentials developed, and Laplace's equation emerged. These prompted much mathematics, elliptic coordinates and a variety of new mathematical functions.

cannot be orbital motion of planetary bodies and in stellar galaxies. Masses from the primordial Big Bang would have splintered helter-skelter along divergent paths, receding away independently for as long as time will tick.

Action at a Distance: *A push or a pull without touching.*

Try to exert a physical effect on something without touching it directly or indirectly, and you are likely to fail miserably. There is really no way one can exert a force to cause any motion except by making contact with it one way or another, whether by placing our hand or foot on it, or with strings or sticks or whatever. This is what prompted the philosopher Thomas Hobbes (1588–1677) to declare[6] in the seventeenth century, before Newton's gravitation was proposed: "There can be no cause of motion in any body except it be continuous and moved." Any other mode of causing change of motion would be action at a distance. Once upon a time, people described such action as magical. The book publisher Henry Holt called it *telekinesis*.

So it is not surprising that when Newton audaciously proposed it, some of the best minds of the time were not exactly enthusiastic. Voltaire informed people that for forty years after its publication in 1687, barely a score of scientists took gravitation seriously. For the next two centuries many critical minds found it difficult to accept the idea of some kind of influence propagated by inanimate matters through the abyss of empty space[7]. Newton himself was hesitant about it. In a letter to Richard Bentley (1693) he wrote[8]: "It is inconceivable that inanimate brute matter should, without mediation of something else which is not matter, operate on and affect other matter without mutual contact. ... That gravity should be innate, inherent and essential to matter, so that one body may act upon another at-a-distance, through a vacuum, without the mediation of anything else by and through which their action may be conveyed from one to another, is to me so great an absurdity that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it. So far I have explained the phenomena by the force of gravity, but I have not yet ascertained the cause of gravity itself. ... and I do not arbitrarily invent hypotheses."

But once its powers were recognized, one could not brush off the idea as some crackpot attempt to bring back invisible angels and spirits back into decent physics. When the idea is cast in its

6 Hobbes, Thomas, *The philosophy of Hobbes in extracts and notes collated from his writings*, The H W Wilson Company, London, p.60, (1903 ed.)

7 Descartes, Huygens, and Leibnitz, all thought that action at a distance did not make any sense. See in this context, Maglo, Kofi, The Reception of Newton's Gravitational Theory by Huygens, Varignon, and Maupertuis: How Normal Science may be Revolutionary, *Perspectives on Science*, Vol.11, No.2, pp.135–169, 2003.

8 Quoted in I B Cohen, *Isaac Newton's papers and letters on natural philosophy and related documents,* p.302, Cambridge University Press, 1958.

mathematical mold and explored, you can squeeze out of it all the laws of Kepler on a clean sheet of paper. If no one had ever seen a planet in high heavens, one could still have said how they ought to be moving and how fast by simply working out the consequences of the gravitational laws. So here is this mysterious action at a distance (or *actio in distans* as it used to be called in Latin) which no one likes to accept, but which, if accepted, explains so many things, including when Halley's comet will appear again.

That, in effect, is how physics works: Give me an idea from which some aspect of perceived reality can be explained, and I'll buy it, even if it seems somewhat weird to begin with. We see the effect of gravitation every day and night, all around us and in the universe at large: gravitation propagated without the benefit of a material medium. Yet, we are unable to concede that this can be so. We want something in between so that a force can be transmitted through a so-called medium. But we see this happening all the time around us, and we are not in the least surprised. When the vase falls down from the table, or the apple from the tree, there is no contact with the descending body. We speak of gravity so glibly, of the sun making the planets whirl around it as if it had ropes tied to them. It is no mean puppeteering that the sun does, pulling bodies millions of miles across space. There seems to be something spooky about this gravitational act.

Often we extrapolate from common experience to fantasize entities, processes, and other worlds that just do not exist. But with gravitation there is nothing familiar from which to extrapolate: hence the difficulty.

Gravitation and Stars: ***Gravitation is responsible for the birth and death of stars.***

Strange as it may sound, the sun and the stars would not have come about without gravitation. For these are gradual massive accumulations of matter, allured over eons to mutual adhesion, primarily through the gravitational force. It is gravitation that compressed matter of mammoth magnitudes and thus generated temperatures high enough to induce the nuclear fusion necessary to set stars aglow. We often think of the sun as the source of all our energy. True, but the sun could not have been formed without gravitation. This is a most remarkable discovery.

Ironically, it is gravitation again that ruthlessly decimates stars in their old age. With relentless pressure gravitation smashes matter at its skeletal void, transforming stars of ageless shining into white and black dwarfs, pulsars and more. Sometimes they could becomes explosive supernovas whose cores could not tolerate the high pressures any more. But prior to that, heavier elements were synthesized there. When the star is massive enough and conditions are appropriate, gravitation can act with frightening fury and cause a catastrophic collapse which can result in the monstrosity called 'black hole'. In the heart of black holes, space and time are mutilated, and the very laws of physics cry out for redefinitions[9].

Thus we see that the Newtonian picture of gravitation as attraction between massive bodies is effective and adequate in a whole variety of contexts: planetary motions, falling bodies, and stellar evolution. No wonder it ruled the realm of physics for more than two centuries.

Other Functions of Gravitation: ***We are enabled to live on earth, and our earth in the solar family because of gravitation.***

We may not remember when it happened to us, but we see little toddlers trying to stand up and fall. Gravitation is the hurdle that we had to cope with before we could learn to stand upright. It is the string that binds us to our planetary habitat in the universe. Without gravitation we would be flung into empty space. Our planet supports an atmosphere because gravitation holds on to the air molecules in its vicinity. If the earth's gravity were not strong enough it would have no mantle of air. The moon's gravity is too weak to chain air molecules firmly in its vicinity.

Gravitation is the music by which the planets glide in Keplerian orbits, and proximate double stars dance around each other, as do neighboring galaxies as well. More generally, gravitation keeps planets and stars in orbit, and is thus uniquely responsible for the structured orbital patterns in the universe. With all its simplicity, gravitation is still a major mystery. Who can say what possibilities are in store when we unveil her secrets even more?

Modifications: ***Planetary orbits can be viewed without reference to the gravitational force.***

Einstein's wand metamorphosed the conceptual framework of gravitation. As a result of his revolutionarily new perspective, the effects of gravitation came to be understood as resulting from a kink in space-time, a warping brought about by too much mass in the deep fabric of space. Orbits became motions along the shortest paths in a curved space-time, even as uniform motion is merely persistence in Euclidean flat-space. In other words, this cosmic grasp of all that is matter is due to an insubstantial space-time that is twisted and turned by bodies of astronomically massive proportions[10].

Einstein's formulation of gravitation is brilliant, eminently more elegant and mature from a mathematical stand-point. More than that, its interpretation of the bending of light rays in the vicinity of stars has no analog in the older view.

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9 For an entertaining but serious account of stellar evolution see, Clifford A Pickover, *The Stars of Heaven*, Oxford University Press, 2001.

10 This arose from his *General Theory of Relativity*. For a popular presentation of this, see Lillian Lieber, *The Einstein Theory of Relativity: A Trip to the Fourth Dimension*, Paul Dry Books, Inc., Philadelphia, 2008.

Then there are the gravitational waves of the Einstein theory which must propagate through interstellar space, with a silent subtlety that is beyond normal recognition[11]. In principle, gravitational waves may arise from catastrophic events, like supernova explosions, or from periodic processes, as in double or spinning stars. Theoretically, even a spinning rod should emit gravitational waves. Human ingenuity knows no bounds. It concocts ideas and designs devices incessantly. The puniest of perturbations are detected and eventually measured. So with esoteric apparatus and painstaking dedication some have even announced that their instruments have responded to the faintest palpitations of gravitational waves, perhaps from the core of our galaxy, or from the orbital variations of binary pulsars[12].

Interactions: ***Every entity in the material world interacts with some others.***

The gravitational attraction between two bodies is mutual. In accordance with the third law of motion, when one body exerts a (attractive) force on another, this other body does the same. When entities act on one another we say that they *interact*. Interactions are what bind the world as one. Forces are interactions. Interactions cause change. That is to say, they make things happen. They produce phenomena. No interactions, no change, no happenings, no phenomena. The world will remain as it ever was, drab and static, uneventful and actionless. Mere matter cannot keep a world functioning, for functioning involves exertion and dynamism. Gross matter in the universe without interaction would be like lone sculptures in marble, cold and lifeless and dead in the empty arena of space. What a boring world that would be!

Recall that in this world just as there is matter and energy, there is also being and becoming. Being refers to mere existence, and becoming refers to how the existing entities transform. The elementary particles are the substratum of being, and the fundamental actions are at the basis of becoming. So there are interactions everywhere, mutual and multitudinous. There is not a corner in the world where interactions don't come into play. There is not a moment when they cease to act. There is no scale where they are absent: they are there deep down in the minute microcosm, they are there right on our levels of activity, and in the grand cosmic scale too.

Forces like weight and friction, tension and normal contact reaction are what we measure and calculate at our level of experience. They are directly observable, or at least their effects. But how do they come about? They arise from more fundamental features of the world. Their roots lie beneath perceived reality. As we noted earlier, the weights of objects are due to gravitation which is one of the fundamental interactions undergirding the universe. It makes apples fall and

[11] Gravitational waves were first predicted by Albert Einstein in 1916: *König. Preuss. Akad. Wisssch. Sitz.* II, p.688.

[12] In this context, see Harry Collins, *Gravity's Shadow: The Search for Gravitational Waves*, University of Chicago Press, 2004. Thus far the search for gravitational waves have not yielded incontrovertible evidence of their existence. Also, N Cohen, *Gravity's Lens: Views of the New Cosmology*, Wiley and Sons, 1988.

stones to sink; it causes planets to turn, stars to form, and keeps the universe together.

Fundamental Interactions: ***Interactions occur at the ultimate level.***

We have seen that at our normal level of experience, there are only a handful of force types (weight, friction, normal contact force, tension, buoyancy). We can account for all that we observe in the material world in terms of these. Likewise, at the root of physical reality, there are only a few fundamental forces. We refer to these as fundamental interactions.

The physical universe is ultimately made up of countless *elementary particles* which are minute beyond direct perceptual recognition. Their variety is not unlike the plethora of species that constitute the realm of life-forms. Just as living entities act upon one another and maintain a biosphere, the ultimate particles incessantly interact in different ways, giving rise to this marvelous world of perceived reality.

The human mind has tracked down and categorized the number and nature of the fundamental interactions that make things happen in the world. We have already referred to one of them: *gravitation*. There are only three more. What this means is that in terms of these four interactions we can understand every known (physical) feature of perceived reality. These four types of interactions are what make the universe click the way it does. One of the other three bears the epithet: *electromagnetic*. The electromagnetic interaction is due to the existence of electric charges in the universe. It is responsible for countless aspects of perceived reality.

The other two are described by more prosaic, if more intuitively graspable, terms: *strong* and *weak*. The terms *weak* and *strong* might suggest that not all interactions are equally potent in their effects. This is not the case. The terms connote a quantitative feature that has little to do with their ultimate effects, but has to do with the contexts where they come into play. If we list fundamental interactions in terms of pure strength alone, gravitation will be at the bottom. It is far, far weaker than the weakest of the other three[13]. Yet, and this is the marvel, its embrace extends to distances that are infinitely greater than how far the strongest of the interactions can exert. Just consider the sway of the sun over the planets in its system at millions of miles away, or of galaxies separated by light years which are bound to one another. On the other hand, the strongest of the interactions barely extends beyond the diameter of atomic nuclei.

Sources and Conveyors of Interactions: ***Fundamental interactions are associated with specific features of the physical world.***

For every interaction there is a *source*, and that source is the only entity involved in that

[13] If the strength of the gravitational interaction is taken as 1, that of the weak interaction will be 10^{25}, of the electromagnetic 10^{36}, and that of the strong interaction 10^{38}.

interaction. Thus, mass is the source of gravitation. That is to say, every entity or body endowed with mass exerts a gravitational force, and such an entity or body is also subject to a gravitational force. Likewise, every electric charge is the source of the electromagnetic force, and it is also subject to that force. The constituents of every atomic nucleus are the source of the strong interaction and they are also subject to the same. The so-called leptons are the source of the weak interaction, and are affected by it also.

Interactions between the fundamental entities of matter are brought about through the exchange of certain other kinds of fundamental entities. These are known as field bosons[14] or field particles. The field particles for the gravitational interaction are known as *gravitons*, those for the electromagnetic interaction are the photons. These force conveyors for the strong interaction are called quarks, and the ones causing the weak interactions are the W and the Z particles.

Unified Field Theories: ***We may be able to derive the four interactions from a smaller number.***

Two questions might arise in the context of our exploring fundamental interactions. First, are there other fundamental interactions of which we are not yet aware. One cannot answer this question, because who knows what is in store for the future. But this much physicists are sure of: Practically every known physical phenomenon thus far can be traced to one or other of the elementary particles and the fundamental interactions.

The other question is: Just as the cause of the falling apple and of the orbiting planet could both be unified into a single interaction, namely gravitation; and just as electrical and magnetic phenomena could both be unified into a single electromagnetic field; could we perhaps unify some of the known four fields to get a smaller number of fundamental interactions?

This has been attempted, and borne some fruit. Einstein and his disciples in their heyday tried to unify the gravitational and the electromagnetic fields, but to no avail[15]. But one of the major triumphs of twentieth century physics was to unify the weak and the electromagnetic interactions. Those who are engaged in this quest feel confident that one day we will be able to formulate a theory which would unify all the known fundamental forces. We would have a final theory: a Theory Of Everything (TOE)[16].

[14] The term *boson* is derived from the name of the Indian physicist Satyendra Nath Bose (1894–1974).

[15] Physicists who investigated this in the first third of the twentieth century included Albertt Einstein (1879–1955), Theodor Kaluza (1885–1954), and Hermann Weyl (1885–1955).

[16] See in this context, Steven Weinberg, *Dreams of a Final Theory: The Scientist's Search for the Ultimate Laws of Nature*, Vintage, 1991.

No one can say for sure when such a final theory will come to pass. As Steven Weinberg said[17], it "may be centuries away and may turn out to be totally different from anything we can now imagine"

Some have asked, what bold self-assurance is this? To imagine we will one day – and in the not too distant future, according to some – have the golden key that would unlock every secret that Nature holds? How presumptuous of finite minds, they ask, to believe they can compress the infinite variety into a few compact concepts and computations? How utterly arrogant that we can even fantasize about such a possibility? Do not our data change, and our frameworks and our insights from generation to generation? How can we ever talk of the final word?

And yet, this is the optimism and the unbridled ambition of the human spirit: to march forward in a quest that may never end, and never be stunted into inactivity because the goal seems distant or impossible to reach. Or, to borrow from the lyrics of Joe Darion (*Man of La Mancha*): "To dream the impossible dream and to try to reach the unreachable star." When this spirit is stifled there can be no science, no emergence of new insights, and no uncovering of new truths. The wisdom of the ancients was achieved by men and women who thought in such bold terms, not by those who merely repeated with pride what their ancestors had declared to be the truth.

Right or wrong, every generation of scientists has been optimistic about the eventual success of their discipline to unravel every mystery of the natural world, even though as individuals all physicists know that our language and imagery are bound to be modified with the passage of time and the acquiring of more knowledge. But we must advance through the tunnel, believing there is light at the end. That is the spirit of science, that is the spirit of physics.

[17] ibid. p. 211.

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Previous Parts:
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