

# Historico-Critical Analysis of the Concept of Mass: From Antiquity to Newton

**Mashood K.K.**

*Homi Bhabha Centre for Science Education (TIFR), Mumbai, India*

*What is carried out in this paper is a critical analysis of the conceptual evolution of 'mass' from antiquity to Newton, showing how the concept has evolved out of the givens of experiences at various phases of human thought. The current significance and relevance of topics like this with regard to physics education is also discussed. The story of mass starts its course with the earliest notion of 'measure of matter' which coincides with the measure of food, around the dawn of agricultural age. Matter, although intuitively obvious was an intractable morass for the thinkers that followed. The adumbrations in neoplatonic philosophy, followed by its mystic and still inarticulate presentation in theology gradually paved way for its manifestation in the physics of Kepler and Newton.*

## Introduction

The conceptual edifice of physics is indisputably an imposing structure, so much so that it has attained an aura of permanence. This façade of permanence has, regrettably stymied the historical awareness and the metaphysical curiosity of the present day physicist. A careful perusal of the present crop of physics text books will attest to the fact that the historical travails of the architects of this magnificent edifice are given rather short shrift. Emphasis is laid on the algorithmic approach. This can have damning consequence for the whole culture of physics. A scientist brought up in the algorithmic tradition will be deterred from taking the whole edifice brick by brick, turning them over and going through them with a fine tooth comb, the way the past masters have done. Conceptual stagnation would inevitably follow. This should not come to pass. The antidote would be to revitalize the cultural approach. It is with

this intent that the present work has been carried out. In particular we trace the genesis and evolution of the concept of mass from the dawn of the agricultural age, through the prehistoric times and antiquity right up to its final efflorescence in Newtonian physics.

## Evolution of the Concept of Mass

### *Pre History*

It is quite likely that the notion of a 'measure of matter' first took shape in the geographical region contiguous with the present day Syria and Iran, at the dawn of the agricultural age (which is roughly 6000 BC). A natural motivation was the problem of apportioning the harvest equitably among the masses. The distinguished metrologist Livio Stecchini states (Stecchini, 2008) that the ancient rule was that an adult 'free' male consumes two basic pints (540cc) of wheat a day. Women and slaves usually received half of this basic ration. A basic pint is equivalent to the contents of two hands cupped together. This handful is the first actual measure for volume and corresponds roughly to the modern cup. Throughout the ancient world the bare survival ration was recognized to be a basic pint (270cc, about 700 calories). This makes it abundantly clear that the earliest notion of 'measure of matter' coincides with the 'measure of food'. At times of famine when the only thing that mattered was food, a clear appreciation of the measure concept was essential for survival.

Another measure available for the quantity of matter was the weight. Balances were in common use in ancient Egypt, as testified by the Nile Papyrus manuscripts (Jammer, 1964,

p.16). However the ancients regarded weight as an intrinsic property of a body like color or odor rather than a dynamical quantity like force. Consequently for different kind of goods different units of weight were used. Next we trace the etymology of the modern ‘measure of matter’, that is ‘mass’.

### ***Theological and Metaphysical Roots***

In physics the word mass or its Latin equivalent *massa* came into common usage at the beginning of the 17th century. In his *Lexicon technicum*, John Harris states that “Masse, this word is used by the natural philosophers to express the Quantity of Matter in any body” (Jammer, 1964, p.7). In Latin *masse* means a lump of dough. Slowly the notion was generalized to signify a lump of anything. The Latin *masse* is derived from the Greek *maza*, where it means barley cake. In the ancient Greek literature *maza* denotes a kind of bread inferior in quality to the wheaten bread (*artos*).

If we delve a little deeper into the etymological roots, then things get somewhat murky. Divergent schools of thought emerge. One view is that the Greeks borrowed it from Hebrew, where it connotes unleavened bread. A dramatically opposite view is that the Cretan term found its way into Hebrew – courtesy the warlike Philistines.

Anyway the exact order of precedence is immaterial as far as physics is concerned. Stepping back into the stream of ideas that wend their way through, to the modern notion of mass, we see that the trail leads us inevitably to the Bible. The Old Testament is replete with instances wherein fermented bread is proscribed and instead the unleavened *maza* approved in relation to certain sacrificial rituals. Fermentation was equated with putrefaction and regarded as symbolizing moral turpitude or corruption. According to Mathew 16:6, Christ says “Take heed and beware of the leaven of the Pharisees and of the Sadducee’s”. Thus it is widely held by the Christian theologians that it was the unleavened *maza* that was consumed at the last supper. The fact that during the re-enactment of the last supper in the Christian ritual of Eucharist unleavened bread is served, lends further credence to this view. It is pertinent, in the context to note that the very name of the Eucharistic service is ‘mass’.

### ***Matter***

Although intuitively obvious, philosophically this is an intractable morass. As far as definitions go, an entity may be regarded as the totality of all its qualities. The domain of physics is restricted to the quantifiable aspects of these qualia. Measures are invariably related to the quantifiable attributes. Thus the term quantity of matter is meaningful

only in relation to an attribute of matter. The ‘quantity of matter’ is pinned down by measuring one of its attributes. Analytic philosophers would argue that the phrase ‘quantity of matter’ is a category error (*contradictio in adjecto*). In classical physics, by a fortuitous happenstance ‘inertia’ and gravitational charge were the chosen qualities. Both lead to the same quantification. On the other hand inertia and heat capacity or inertia and capacitance would lead to confusing and divergent results.

Now there is a way around the philosophical objection of category error, provided we assume that matter is made up of indivisible, countable, building blocks. Then depending on the number of blocks contained within a body, matter may be quantified (just as a pint of wheat is constituted of a countable number of grains). Such an idea of indivisible entity was prevalent in ancient Greece (Democritus). However this did not motivate them into positing quantity of matter. The reason is that the ancients under the somewhat stultifying influence of Plato maintained that magnitude, shape, resistance and weight are just forms and not the substratum that accepts the forms. Matter was regarded as an absolutely passive, inert and inactive substratum, whose sole purpose was to provide a venue for the myriad of forms (Plato). Thus quantification is regarded as an artifact arising from the introduction of forms (a boundary condition). This view should warm the cockles of a modern physicist’s heart. Quantum mechanics regards quantification as the result of an operation (again boundaries imposed by the measuring apparatus).

Incidentally a form of theistic atomism was developed by the Vaiseshika School of philosophy in ancient India. Kanada who lived in the 6th century BC was the major proponent. Etymologically matter has its roots in *materia* or *materies* which in turn stems from *mater*. *Mater* means the ‘source of growth’ (mother). *Materia* originally meant timber. This terminology is indicative of the Aristotelian philosophy underlying visualization of physical phenomenon. Matter was regarded as an organic continuum with growth and decay, increase and decrease of substance. Invariance and conservation were never suspected. In Aristotelian view the growth and decay are compatible with the preservation of identity of the substratum.

Clearly the ancients though in possession of the barley cake (*maza*), volume and weight never thought it befitting their philosophical predilections to posit a measure for the quantity of matter qua conservation and invariance. The later Judaeo-Christian theologians found some of the tenets of the Platonic philosophy to their liking, especially its inertness and absence of forms. Form, life and activity could then be ascribed to divine intervention. Rather ironically

this demotion of matter into an inert impotent entity aimed at supplanting it with a spiritual, immaterial reality turned out to be the undoing of the theologians and it in fact led to the rise of the materialistic, scientific world view in the West.

In his treatise *Maqalah fi al-jirm al-samawiy* (1178 AD, *Concerning the substance of the celestial sphere*), Ibn-Rushd states (Jammer, 1964, p.38) that prime matter, independent of substantial form, must be endowed with divisibility or quantity. The logic was that different objects of the same substantial form existed. Clearly these identical objects would serve as a measure. Ibn Rushd maintained that there are two kinds of dimensionalities associated with matter - the 'determinate kind' and 'indeterminate kind'. The former was regarded as something which exists in the latter. This is in the tradition of the Aristotelian view that there are things which exist in themselves and those which exist in others. The second one is called an 'accident'. During the time of medieval philosophers (8-13th century) the conception of matter had evolved from the completely attribute-less prime matter to one which was a combination of form and prime matter. This was called elementary matter. The specific form was called *Forma Corporalis* (corporeal form).

*Elementary matter = Prime matter + Form*

Thus it became necessary to relate '*Forma corporalis*' and 'extension' or volume. This is the reason why Ibn Rushd posited an indeterminate three dimensionality and a determinate three dimensionality.

Now one of the problems the 12<sup>th</sup> century Christian theologians had to contend with was the reconciliation of the Aristotelian notion of substance and accidents, with the Christian dogma of transubstantiation (scholasticism), according to which the whole substance of the bread changes into the flesh of Christ (and wine into blood) during the Eucharist. Aegedius Romanus (13th century) at the University of Paris, a disciple of St. Thomas Aquinas, borrowed Ibn Rushd's doctrine of determinate and indeterminate dimensions, to explain the thaumaturgical aspect of transubstantiation. Romanus argued that (Jammer, 1964, p.45) in bread and wine and for that matter all earthly matter there are two kinds of quantities. Ibn Rushd's indeterminate dimension is now *quantitas materiae* and determinate dimension is volume. Romanus goes on to argue that the variation of one of them does not imply the variation of the other. For example in rarefaction determinate dimension increases while *quantitas materiae* is unaffected. No natural force could affect the indeterminate dimensions. (Recall that in Newtonian physics we deal with a point mass without any spatial extension). In other words indeterminate dimension

is a conserved quantity. For the first time a measure of matter quantitatively different from volume had been posited.

Jean Buridan (14th century) built his impetus theory around the notion of *quantitas materiae*. According to this the more *quantitas materiae* a body possesses, the more receptive will the body be to an impetus. In Galileo's '*Dialogue on the great world systems*', Salviati asks "whether there is not in the body.....intrinsic and natural quality which makes it averse to motion".

It was Johannes Kepler who came up with an unambiguous delineation of the inertia concept in his *Epitome astronomiae Copernicanae*. He states (Jammer, 1964, p. 55) "Every celestial sphere, because of its materiality has a natural inability to move from place to place, a natural inertia or rest whereby it remains in every place where it is set by itself".

"If the matter of celestial bodies were not endowed with inertia, something similar to weight, no force would be needed for their movement from place to place; the smallest motive force would suffice to impart to them an infinite velocity. Since, however, the period of planetary revolutions take up definite times, some longer and other shorter, it is clear that matter must have inertia which accounts for these differences". In the second passage clearly a metaphysical notion changes its hue to a physical reason.

Kepler goes on, "the transporting power of the sun and the impotence of the planet or its material inertia strive against each other". Thus inertia of a body is not only the inability to transport itself from place to place but is also a tendency to resist any external influence. "Inertia....it is stronger, the greater the quantity of matter in a given volume"; clearly Kepler has identified the connection between inertia and *quantitas materiae*. Kepler however never realized that the same inertia can account for the continuity of motion, once it is imparted to a body.

Here we see the Comtean (Augustus Comte) view on the evolution of concepts, being played out right before our eyes. August Comte maintained that a concept evolves through 3 stages- namely a theological, a metaphysical and finally a scientific (physical) phase. With the above mentioned pronouncements, Kepler succeeded in liberating inertia from its metaphysical underpinnings and elevating it into the last rung of the Comtean ladder. [Incidentally, the notion that slow moving planets are heavy was widespread in Hindu astronomy. For instance Jupiter which takes about 12 years to orbit the sun- was called Guru. Guru means ponderous or heavy].

### *Mass as a Scientific Concept*

Once a concept leaves its theological and metaphysical shibboleths behind, it has to run the gauntlet of systematization and formalization. Systematization is the process wherein the new concept is incorporated into the grammar of the scientific system. It starts functioning as a connective between observation and explanations. In the final stage of formalization, the concept assumes a formal role within the deductive system. In this final abstract form, it is devoid of any interpretative meaning other than that afforded by its relation to the rest of the formalism. Rules of correspondence are then provided which correlate the formal entity with the corresponding physical entity. (A well known exception is quantum theory. There the formalism came before the conceptualization.)

Although Kepler succeeded in conceptualizing the notion of mass, further progress in the systematization was hampered by the rise of Cartesian intellectualism. Descartes was completely opposed to inertia or tardiness in matter. According to him, the defining characteristic of matter is spatial extension. The geometry and *quantitas motus* (momentum) regulate the physical behavior. Obviously the Cartesian scheme fails the experimental test. (A solid sphere and a hollow sphere of same radii move differently when placed on the same inclined plane). However, Descartes' stature as an intellectual giant, succeeded in intimidating into submission, the opposing camp. It took another fifty years before the Cartesian viewpoint was conquered by an equally forceful work of Christian Huygens: *Horologium Oscillatorium*. Huygens noted that when particles move with equal speed along circles of equal radii, the ratio of centripetal force equals the ratio of the weights, or 'solid quantities'. By solid quantities, Huygens obviously means the masses. Again in the analysis of collision between two objects, Huygens lays down the following conclusions (Smith, 2006, p. 33).

1. The sum of the products obtained by multiplying the magnitude of each hard body by the square of its velocity is always the same before and after collision.
2. A hard body at rest will receive more motion from another larger or smaller body if a third intermediately sized body is interposed, than it would if struck directly, and most of all if this (third) is their geometric mean.

Apparently the magnitude is *quantitas solidas* and the geometric mean is the mean of their masses and not volumes. To recapitulate, the Keplerian notion of inertial mass succeeded in functioning as a connective between observations and explanations in three major instances:

1. Difference in time periods of planetary orbit (albeit flawed).
2. Dynamics of rotational motion.
3. Impact experiments.

Having established its antecedents, it is quite unsurprising that the theme segues its way into the work of Newton. It is not for nothing that Newton states that he has seen farther by 'standing on the shoulders of giants'.

Newton adopted the Keplerian idea that the inertia is stronger, the greater the quantity of matter. Moreover, Kepler's attempt at an operational definition of inertia too was incorporated without any significant change. Kepler had argued that planetary bodies are endowed with something like weight akin to terrestrial material bodies. Specifically he attributed to them a resistance to motion which is determined by the volume of the body and density of matter. (Density determination was by the standard method by immersing the body in water. Clearly this tacitly assumes that inertial mass is proportional to weight.) However Newton was careful enough to distinguish between *quantitas materiae* and *vis inertia*. He merely assumed a proportionality between the two. In Newton's theory of gravitation, it is the former that determines the magnitudes of gravitational attraction. Newton carried out a series of experiments with pendulum bobs of different materials - wood and gold- but equal weight. He noticed that the period of oscillation was independent of the choice of the bob and depends only on the length. That is in modern notation

$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$w = mg$$

$$T = 2\pi\sqrt{\frac{ml}{w}}$$

$$\frac{m}{w} = \frac{T^2}{4\pi^2 l}$$

The ratio of *quantitas materiae* to the weight is found to be a constant. Newton was also aware of Jean Richter's experiments regarding the variation of weight with location. This led to an appreciation of the distinction between weight and mass ( $w = mg$ ). Establishing the proportionality of  $w$  and  $m$  was a crucial step in the systematization of mass. Any arbitrary body could be chosen as the unit of *quantitas materiae*. All others could be determined in terms of these, by weighing on a simple balance. It would not be far-fetched to state that for Newton the fundamental physical notion was that of *quantitas materiae*. All other manifest attributes

like inertial mass, gravitational attraction and weight could be reduced to this theological - metaphysical concept.

Newton's concept of mass was subtly influenced by the revival of Atomism in the 17th century. Since different objects of the same volume exhibited different *vis inertia*, Newton summarized that they contain different quantities of matter. This made sense only if one posited an intensive, volume independent attribute. This intensive attribute should apply down to the smallest constituents of matter since inertia was believed to be universal. This irreducible attribute was the density. In *Opticks*, Newton states that "God is able to create particles of matter of several sizes and figures, and in several proportions to space and perhaps in different densities and forces". Force means *vis inertia*. In the final count, the theological-metaphysical *quantitas materiae* is linked to the measurement of the conjoint of an intensive and an extensive attribute (density and volume), the extensive attribute being manifest and the intensive one required by the philosophical predilection that inertia be a universal trait.

So when the black plague forced Newton to take upon himself the task of setting the house in order, he had before him an embarrassment of riches – *vis motrix, quantitas materiae, quantitas solidas*, acceleration, density, *quantitas motus*, volume. The genius of Newton lies not so much in that he organized this cornucopia of concepts but in his brilliant choice of the mechanical state of a system. Following the footsteps of Galileo he realized that rest was just a special case of uniform motion with  $v=0$ . Thus the 'natural' state of a mechanical system is characterized by its momentum,  $p$  and not necessarily by the rest. Unencumbered with the baggage of the Scholastic position, '*cessante causa cessat effectus*', Newton could now pose the correct question as to the cause upon which the change of state is predicated.

## Conclusion

In the story of mass (from the point we ended above) miles had been traversed thenceforth by the best of scientifically curious minds. While in the theory of gravitation the con-

cept was merely extended, relativity both special and general brought far reaching changes in the meaning of the concept itself. At present with the multi-million dollar experiments with high energy accelerators going on and topics like 'mystery of lepton mass' and 'Higgs boson' (Hobson, 2005, p.81) etc., on the scientific table, the concept of mass is awaiting far more. The essential prerequisite for such things to happen has become a rare 'commodity'. Dearth of creative and imaginative minds in physics at present or at least in future has already become a topic of much discussion. History of physics gives ample evidence for the fact that revolutionary breakthroughs in understanding nature were mainly possible by the contribution of those scientists, who had in depth insights into the core issues of the subject. And let us not forget that philosophical, historico-critical analyses, etc., were among the key weapons in their armory. In addition to imparting such skills to the future scientists, introduction of topics like historico-critical analysis of concepts in the curriculum would greatly help in the treatment of emotional aberrations of various sorts which is becoming a hallmark of modern technological society.

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