Teaching Physics – What are we trying to do?
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Science Dynamics

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> 'The soul, then, as being immortal, and having been born again many times, and having seen all things that exist, whether in this world or the world below, has knowledge of them all; and it is no wonder that she should be able to call to rememberance all that she knew . . . for all enquiry and all learning is but recollection.'[1]

Plato and Socrates may have been convinced that we do, in fact, really know everything. Even if this is so, the problem remains of finding the right way to jog our memories so that we consciously know. To do this, we usually find a teacher, or, for most people, as students, a teacher is found for them. The teacher, therefore has the role of either guiding the student to self-discovery or, implicitly rejecting Plato and Socrates, and lecturing to the student, in the belief that the student is appropriately prepared for the sorts of explanations given in the lecture.

In this paper I shall not explore in any depth the direction of self-discovery, which could be described as a process of 'internal communication', but rather, focus on the process of 'external communication', where a second person ie a lecturer is involved.

How often has one heard the cry from students 'he (the lecturer) obviously knows his stuff but I can't follow his explanations'. Again, in this paper I am not interested in the many problems of inarticulate teachers or deaf students. I will focus on the process of explanation, and endeavour to develop a schema, which can be used to understand that student's problem.

To develop this schema, we need to define some of the terms that are so often taken for granted.

First, <u>knowledge</u>: the student is trying to become knowledgeable, we are trying to impart knowledge, or lead the student to knowledge, or to a state of knowing. Webster's defines knowing as:

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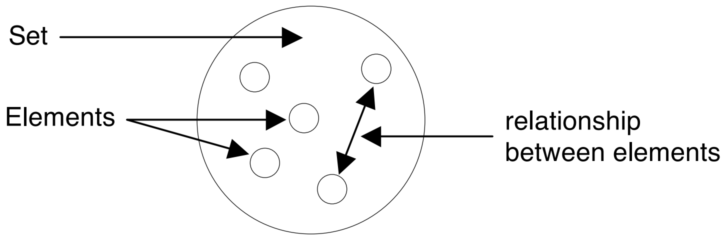
[1] Plato

> 'to perceive or apprehend immediately by the senses or by the mind; esp. to perceive or apprehend as familiar or intelligible; to recognise; to discern the character of; hence to recognise as distinct from something else . . . etc.'

In this situation we could perhaps see knowing as 'an ability to name things, and to describe or name the relationships between the various parts of that thing, and/or its relationship to other things'.

I will frequently use the ideas from set theory in this paper, and in this case, we can describe knowledge as an ability to name the various elements of a set, and for the relationships between the various elements in the set. The following picture may help:



This immediately leads to a working definition of a FACT, which can be defined as a quantum of knowledge, that is, a statement about the existence of an element, or the relationship between two or more elements in a set. We could express this as:

F = Ei

or

F = Ei ® Ej

where:
F = apples
Ei, Ej = elements
® = relationship

A concrete example would be:

That is the ground

That is an apple tree

That is a ripe apple

or

Ripe apples fall to the ground

where:
Ei = ripe apples
Ej = ground
® = relationship

By being able to state that a certain object is a ripe apple, and that it will fall to the ground, we, are said to have some knowledge about apples, and also some knowledge about the ground. We can nominate each, that is, distinguish it from something else, and state a particular relationship between the apple and the ground.

We can now move on to the more intriguing problem of trying to determine the meaning of the statement:

‘<u>WHY</u> do ripe apples fall to the ground?’

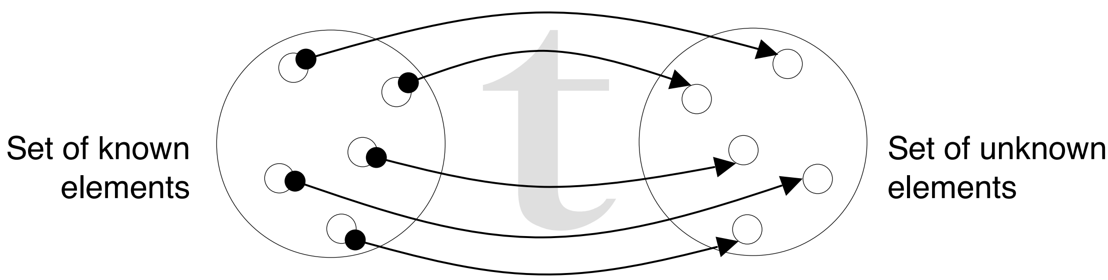
What does this mean? The questioner has asked for more than a simple fact, he wants to know about the spatial and temporal sequencing of this fact, that is the series of facts that precede the occurrence of this relationship or the relationship between this element and other elements.

The student who has asked ‘why’ is said to ‘understand’ when he can recite the sequences or relationships for example the student might say:

> ‘When the force due to gravity acting on the mass of the apple is greater than the tensile strength of the stem of the apple then the stem will break and the apple will proceed towards the ground at a rate determined by the gravitational force’.

For this, we would give him full marks for understanding. But a problem may arise. Perhaps the student did not know why, and the teacher stated the above to him, and he still looked quizzically and said ‘But why?’ or ‘I don’t understand what you’re saying’. The teacher would then perceive himself as having to EXPLAIN the situation to him. The nature of EXPLANATION will be the substance of the rest of this paper.

When we are explaining something, we are in essence developing relationships or connections between what the student knows, and what he doesn’t know. For example, he doesn’t know why the apple falls at a particular rate, so we say ‘. . . it falls at a rate determined by the gravitational force’. We have assumed that he knows what a gravitational force is. So putting this in terms of our set theory, we can describe this *process* of explaining as a *mapping* of the elements of one set into the elements of another set which are:



The *art* of explanation is then to find an appropriate transformation function that maps one set into the other. This is usually appropriate and well-chosen words and symbols.

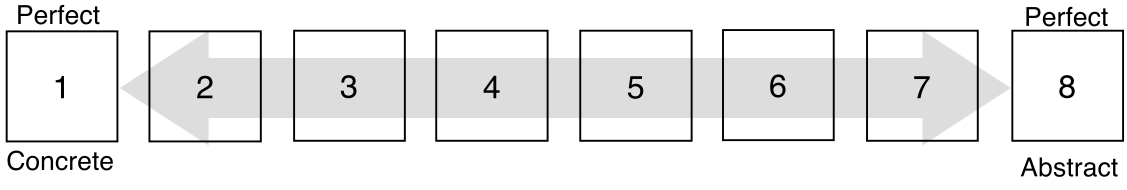
In the above case the explanation may, or may not be satisfactory, depending on the knowledge of the student. If the student knows about the concept of gravitational force and all of its implications, then this explanation or alternative set of concepts may be sufficient. If not, then the teacher has to find an alternative set. We will explore these alternatives shortly.

First another look at that mapping from one set into another is necessary. In the above case the teacher had somehow assumed that the student knew about gravitational forces, or was trying to appeal to the fact that some generalised abstract universal concept prevailed. With such a statement, the student hardly has any greater knowledge of the world, or a greater ability to nominate relationships between elements. The one abstract statement about gravitational force, by itself is rather useless. An alternative would have been to say ‘apples fall to the ground because that is the nature of apples on trees’. We are still appealing to something more general than this particular instance, but we have kept the concept level at about the same level as the question.

We now come to the central idea of this paper. Everybody is familiar with the concept of greater and lesser degrees of abstraction or lesser degrees of abstraction with age. The work of Piaget is based on this idea, and he describes how children usually develop greater abilitites of abstraction. The idea developed here is not intrinsically age dependent, although it can be used to describe child development. I have found that we all use differing levels of abstraction, and we find that different groups have different preferences for different levels.

This is the focal point of the theory: that abstraction is not an infinite gradation but has a finite number of grades. In the case of physics – the description of the physical world, I hypothesise that there are 8 levels of abstraction, and only 8 levels.

We can set them out like this:

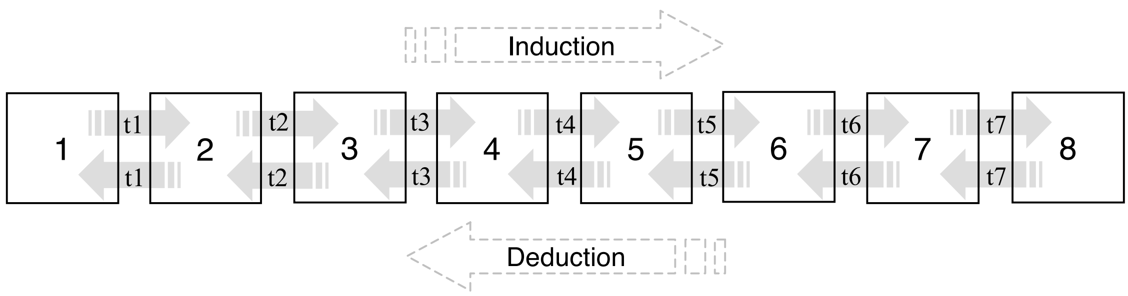


Each of these levels can be thought of as a set, complete with its own elements, and relationships between those elements.

A complete description of the world is possible within each set, but the notion of greater ‘abstraction’ implies a smaller set. If it is to be a complete set for real-world descriptions, there must be something special about the relationships between the elements.

By increasing abstraction, we mean an increasingly generalised set, whose elements and relationships look less and less like the elements of the commonly perceived physical world. At the one end of the scale we have a situation of perfectly ‘concrete’ thought, or description, and at the other end we have a perfectly ‘abstract’ form of thought or description. In between states one and eight, the descriptions look something like ‘reality’, but at each step a little more removed.

Before looking at these eight steps in detail, we need to look at the purpose of them. If, at any stage, the student requires an explanation, then we first try to find a level of abstraction that he has mastered. The teacher then proceeds to a series of mappings to more abstract levels or sets. In this process the teacher is appealing to the students apparent desire for more general statements about the world. Eventually, either the eighth level is reached, or a lesser level and the student is ‘satisfied’ that a sufficient degree of generality has been embraced. The teacher then maps backwards toward the more concrete end of the series, to show that the more abstract notion actually does relate to the real, tangible world. The process looks like this:



If the student can then show that he can nominate all the elements of all the sets, and all of the transformations between those elements, and the inverse transformation, then he is considered to be ‘knowledgeable’. Some cultures would doubt this, but this is the way our western teaching works.

A concrete example will now be used to describe these eight levels of abstraction. I have given each of these levels a name that we can refer to.

Level 1 - Zen

The first level is what I call the ZEN level. This level is considered to be perfectly concrete, and is far from trivial. At this level no words are used, no attempts at mapping or analogies are used: simply direct, silent observation of the world. The Zen Buddhists believe that this is the only true way to knowledge, and that all the smart so-called explanations are only an obstacle to enlightenment, or complete knowledge. The literature of Zen is full of stories demonstrating the folly of rationalising about the physical world, and exhorting students to clear their mind for direct observation. The following is a typical example:

Joshu asked Nansen	"What is the path?"
Nansen said:	"Everyday life is the path."
Joshu asked:	"Can it be studied?"
Nansen said:	"If you try to study, you will be far away from it."
Joshu asked:	"If I do not study, how can I know it is the path?"
Nansen said:	"The path does not belong to the perception world, neither does it belong to the non-perception world. Cognition is a delusion and non-cognition is senseless. If you want to reach the true path beyond doubt, place yourself in the same freedom as the sky. Your name is neither good nor not good."

At these words Joshu was enlightened.

The only "explanation" that seems to be permitted in this state is direct pointing to the event. In our example of queries regarding falling apples, all the teacher can do is to point to the falling apple, and exhort the student to observe it until he "knows" the true nature of falling apples. The proof of this, I suppose, is to be able to successfully do whatever needs to be done with apples. Ultimately the non-Zen student has this same goal.

Level 2 - Polaroid

The second stage of abstraction is very important. This is the first stage that is a break from direct reality. I have called this the "POLAROID" stage, as it is a picture of reality, rather than direct reality. If the student asks about apples falling and we try to explain, using level two abstraction, we try to "freeze" the scene, and nominate the various elements in it. By freezing it, we have assumed that the obedient student will follow our game, and believe that the picture has some validity. This is an enormous step away from direct observation. The teacher shows that in the picture, at the moment of falling, the ground, the tree and the apple bear certain relationships to each other. It may seem to be a fairly trivial level of abstraction but it is the first and a complete explanation may be built up by a series of pictures, or even a slow motion movie. An explanation at this level might be "The apple falls from trees because the apple is high and the earth is lower and the apple falls to the earth because it is lower. The apples goes faster as it approaches the ground". This sounds very tautological, that is, stating the obvious, which is just what it is. We will find in fact that all explanations are more or less elaborate tautologies. An explanation like this is generally used for very young children.

Level 3 - Cartoon

Level 3 abstraction is what I call the CARTOON level. In this level, all or most "irrelevant" detail is omitted from the picture. Enough detail is left to determine that it is, say, an apple, a tree and the ground. The leaves on the tree are not necessary, so they are omitted, so are the blemishes on the apple and the stones and grass on the ground. Again, this is a leap in abstraction, as reality does not look like a series of cartoons. The point of this level of abstraction is to demonstrate that it could have been <u>any</u> apple on <u>any</u> tree or <u>any</u> day in <u>any</u> country etc – that is, a greater level of generalisation compared with that particular tree, apple, orchard and so on. Not only is nature frozen, as in the polaroid stage, but it is also simplified. This level of abstraction suggests that experiments can be set up, as the phenomenon does not depend on the particular situation as observed. A typical explanation at this stage might be "Anything that looks like an apple (or may be any fruit) will fall to a lower level, with ever increasing speed. It is easy to see that having grasped this general concept, the teacher can then take the student back to the polaroid stage to show that actual apples behave like this, and then show the student an apple on an apple tree, at the Zen stage, to convince the student. Alternatively, the teacher could go on to the next level of abstraction.

Level 4 - Public

This I what I call the PUBLIC level (I would welcome a better name). This is because it seems to be the highest level of general public explanation. Beyond this level one becomes a student of the subject. Level 4 is characterised by complete loss of irrelevant detail. The apple becomes a circle – as it is extensive it must have mass, the earth is represented by a line, and motion by an arrow indicating direction. The terminology is generalised to words such as "mass" and velocity". It is the highest level of abstraction that still has some physical similarity to the original physical picture, and it is not too difficult to convince most people that level 4 is a reasonable representation of reality – that is, no elaborate code is required to interpret level 4. An explanation at this level might be "When a small mass is unconstrained at some distance from a larger mass, it will move toward the larger mass with a constant acceleration, and therefore an increasing velocity. Numbers may be used and even simple calculations.

In explaining any physical phenomenon, one moves beyond level 4 at one's own peril, and, I believe, this is the point where many explanations break down, as the codes used are not sued in everyday life, so most people are both unfamiliar with the "elements" in the "set" and also with the operations between the elements.

Level 5 – Vector or Geometric

The VECTOR or GEOMETRIC level. This is the first level that is considered "abstract" by teachers, and bears very little resemblance to the appearance of original physical situation. Masses are represented by points, and vectors represent direction, velocity and acceleration. Forces are spoken of, and actual distances measured. The situation is fully quantified and precise answers are possible by manipulation of the geometry. This, interestingly, is the level of most science in the pre-Newtonian world – sophisticated, non mathematical (ie non algebraic) representations of reality. To teachers of physics it seems to be only a small step from level 4 to level 5, but it seems to be one where many people get lost along the way. The operations between the vectors is probably the difficulty, so in "explaining" at level 5, one needs to ensure that the student is fully familiar with these operations. To do this, the transformations between level 4 and 5 need to be spelled out carefully.

Level 6 - Graphical

This level makes further large leaps into abstraction, and is probably the worst developed of all stages. This is the GRAPHICAL level, where the parameters are mapped into Cartesian or other coordinates. This level can still be completely empirical, as the values on the coordinates can be measured from direct observation, and the curves inferred from a finite number of observations. This level still has some tenuous connection with physical reality, as the distances along the coordinates can correspond to directions and magnitudes. However, the curves drawn may (and generally do not) represent the actual path of an object, but the trace of some parameter, either measured or derived. It has great power compared with the vector stage, as unmeasured values can be inferred and predictions can be made. Although it is coded, it is still an analog situation; that is, magnitude on the graph represents the magnitude of some concept. This concrete aspect of this level can allow considerable manipulation of data once the code is known. Unfortunately this level is quite often skipped over in explanations, the teacher going directly from the vector level to the algebraic level. Because the curves can be described by mathematical expressions relating to the variables, it can be used as a bridge between vectors on the one hand and purse mathematics on the other.

Level 7 - Algebra

At this level, all physical resemblance between the original situation and the representation has gone. The symbols do not look like objects, or have any direction or magnitude. Manipulation of the symbols is by an agreed code that does not seem to be suggested by physical reality. Nonetheless it is a well-defined set, with elements and operations and these can be put into correspondence with the features of the Graph stage. Quite often students develop an ability to manipulate the symbols in this set, but cannot “explain physically” what is going on. That is, they cannot map the algebraic set back into a set of lower level abstraction. This level has the well known power of analysis and prediction, but for scientists it is ultimately only “useful” if the manipulations from this level can be transformed back to level 1, where one can point at the apple as it is falling, or say with certainty what it will do as it falls.

Level 8 - Newton

Like Level 1, the assertion of the existence of this level will surprise many. It is the level that goes beyond sets and models of thinking, to the realm of the intellectual processes of genius. It is fairly certain that Newton, or Einstein for that matter, did not use internal cerebral processes that were like levels 2 to 7, but later used these levels to explain their ideas. It is that level of intuitive brilliance that we all might aspire to, but I suspect that it is one of the attributes of genius that one is born with or without. It is similar in many ways to the Zen level, with the difference being that Newton would see the need or value in using levels 2 to 7, and the Zen master would not. Both levels 1 and 8 represent some form of enlightenment, that is, states of complete knowledge.

Having defined these 8 levels, I can now go back to briefly demonstrate their use. For example, if one is asked to explain why the apple moves towards the earth as it does, one can see that it is important to determine the starting, and finishing level of the enquirer, and also what process he wishes to go through. Generally, the student wishes to have the observation set into some generalised framework, to assure him that the world is essentially orderly; that is, there are patterns in nature.

At level 4, for example, the statement that the apple is a small mass puts it into a category of other things about the same size, and that there is an attraction (not a force) between all masses, in this case the earth and the apple. If the student wishes to know more, the teacher can now easily identify whether the student wishes to have more elements of level 4 named – such as the actual acceleration, or the speed at a particular height – or whether the student wishes to proceed to a more general framework, or set, such as level 5, where the observation becomes fully quantified, and geometric and arithmetic procedures can be used for evaluation. (Note that Newton's laws as they are commonly stated, belong to level 4). If the teacher proceeded to level 6 without going through level 5, a full appreciation of the quantification of the concepts may not be developed, and the teacher may find himself "painting in" the concepts of level 5 while trying to hold the student at level 6. As I mentioned before, level 6 is quite often glossed over, and the teacher proceeds from level 5 to level 7, the algebraic stage, because level 5 is fully quantified. The principal purpose of level 6 is to give some visual images of the relationships between the elements of level 5.

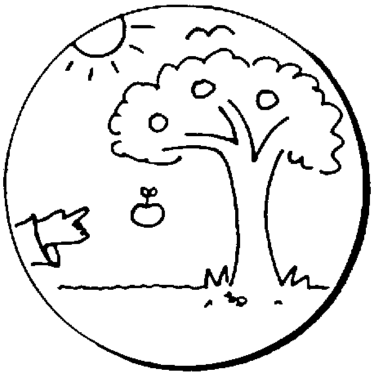
A common problem encountered with teachers is "over-pitching" the explanation, for example, answering the question of the falling apple by saying, "The force between two masses varies directly with the masses and inversely with the square of the distance between the centres of the masses. The acceleration, which is the ratio of the force to the mass of the apple remains fairly constant over the distance between the tree and the ground as this distance is small relative to the distance between centres, which in this case is the distance to the centre of the earth. 'The elements "force", "masses", "distance between centres of masses", and the relationships "varies directly", "inversely with the square", "constant acceleration" etc., may be more than the student knows – ie he cannot confidently nominate all of these elements or these relationships. If the teacher recognises that the student is not happy with this explanation, he can checklist the other levels, knowing now that these levels exist as distinct entities, and find a level at which the student is comfortable, and describe the phenomenon within that level. If the student is happy, but still enquiring, he can proceed to the next level ensuring that the student knows "the rules of the game" of that level, and developing the explanation again, as a relationship between those more general elements.

The general processing of teaching physics, then, is to start with the empirically observable world of the Zen, then, by asserting that continuous observables can be considered as being composed of an infinity of "frozen moments" ie analysed as in level 2, next that many features of the world such as worm-holes in apples, have little bearing on the causal chain in question, and can be simplified as in level 3. Statements about similar features of all observables – such as mass, length and time, and relationships (laws) such as Newton's prevail. In level 5 we assert that measurements can be taken in level 6, that the continuous nature of observables still prevails, and by continuing the curves outside the measured set, that predictions can be made. Level 7 completes the link between the physically observable worked and the world of our own making – mathematics. Implicitly, we are trying to develop the student into a master of the subject where all is comprehended, in level 8. That proposition remains open to debate. To complete the sequence, the teacher shows how new graphs can be generated from manipulation of the elements of algebraic set, whereby new situations can be described with increasing specificity back to the original apple tree.

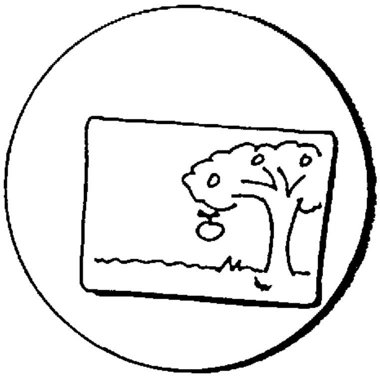
This has been a brief introduction to the idea of the existence of eight levels of explanation in physics. I have not worked it through as yet, but I think that all sciences can be viewed the same way.

This model, I believe can be used to re-formulate many of our ideas in the philosophy of science, even to the point of looking at what philosophy of science is, or is trying to do. I believe that the importance of examining the nature of levels 1 and 8 cannot be over-emphasised. Whether or not we believe that this idea is a new eight-fold way, I think that it can be used as a way of tracing our view of the physical world, starting with the innocent mind of before the Fall, through to the nature of intuitive genius when the Apple fell on Newton's head.

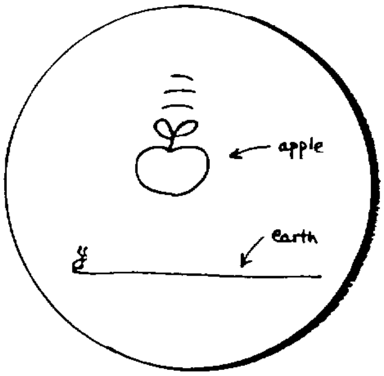
8 Levels of Explanation



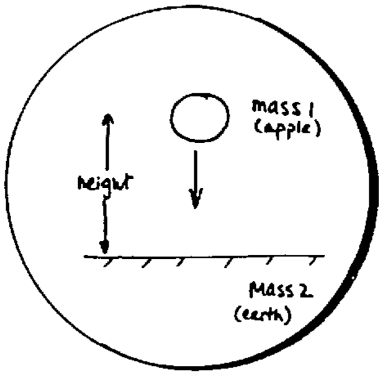
Zen



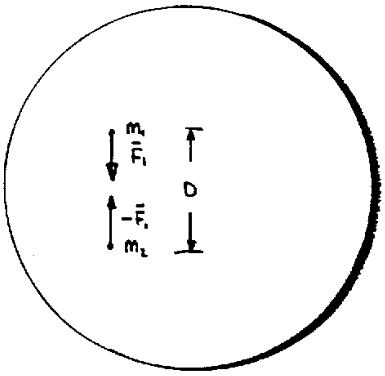
Polaroid



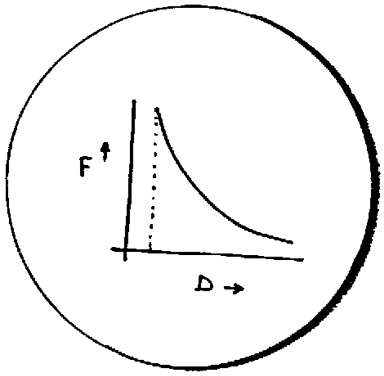
Cartoon



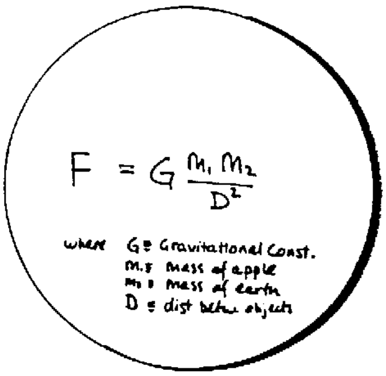
Public



Vector



Graph



Algebra

Newton

How do you explain something that's never existed before?