# 1.4 Physical theories and the program of theoretical physics.

What is a physical theory? It turns out that the answer to this question is a little counterintuitive from the point of view of the general public. A *scientific theory* is a body of work leading to a self-consistent idea that is considered to be a fact. In most cases there is no controversy about the theory in question. So, once again, scientists use a word that public at large thinks is one thing in a different way, thus a miscommunication has developed. The program of theoretical physics is all about developing physical theories. Unfortunately there is more than one such program.

We begin with the modeling approach to theoretical physics. Another way of calling this would be the phenomena-centered approach, whose goal is to understand a specific phenomena by developing model of it, and then subjecting the model to different situations and derermining its properties. The process begins by forming primitive, intuitive, and ill-defined notions about what you are studying. You choose an approach to representing the phenomena; can you represent it as particle? a field? or some continuous distribution of matter? of some combination? From a previous section we can choose either a particle theory, a field theory, or a theory of matter. From this beginning you construct precise ideas and give them symbolic representation. Often the symbolic representations are stated in the form, "Let us assume . . . ." Then you choose a mathematical formulation. Examples of mathematical formulations are Newtonian mechanics, Maxwell's equations, Lorentz transformations, the Maxwell-Boltzmann distribution, etc. You then adapt your mathematical formulation to the specific phenomena you are studying, thus developing a mathematical representation of your phenomena. By manipulating your mathematical representation, making physical arguments and calculations for specific situations, you can make predictions with these activituies—often in the form of tables, formulas, and plots. This might involve deriving new principles and performing computational simulations. This type of prediction is called a *model*. By studying the results in different circumstances you can extend our understanding of the phenomena. A body of models linked by physical argument, derivation methods, and/or computer simulation is a physical theory. This is the most direct method of doing theoretical physics, it is a straight application of mathematical or computational methods. It is certainly the most structured way of doing theoretical physics. Such formulations constitute much of the material of most textbooks and courses on physics.

Another program is the constructive approach to theoretical physics. This can be thought of as the method to develop a new formulation of a physical theory. Examples are the Lagrangian formulation of mechanics, the Lagrangian formulation of electrodynamics, the Eulerian formulation of fluid dynamics, the path-integral formulation of quantum mechanics, and so on. You begin by choosing how you represent objects in your developing theory. Then you choose some quantity, or set of quantities to base your construction on. Then you choose an argument to base your construction on. Are you seeking to find symmetries? Are you arguing from some conserved quantity? Are you assuming that your quantity is minimized? For example, in the Lagrangian formulation you choose to create a new quantity called the Lagrangian and then you work out the consequences when some quantity based on the Lagrangian—the action, for example—is minimized. This leads to the Euler-Lagrange equations of motion, a new formulation of classical mechanics. This is a much more difficult, but powerful method—you build the formulation. The difficulty stems from the lack of structural guidelines in creating a new formulation. Once you have the new formulation, it is actually easier to use in most situations.

A third approach is that of abstraction. Here you take a number of specific cases and generalize their results. For example, knowing that when a rate-of-change is 0 a quantity is unchanged; you take the zero-rates-of-change of momentum in many cases and generalize that into the statment that the quantity of momentum doesn't change—a statement of the law of conservation of momentum. This sort of activity is very difficult since there are few guidelines for how to proceed beyond what is already known.

A fourth approach is to simply play with ideas. Here we are on new ground, there are few guidelines for such play. We can ask, "What happens if we introduce a higher dimension? A lower dimension? Multiple bodies? Fewer bodies? and so on." You can even note the similarity in words describing things. Scientific discoveries have been made with all of these.

The last case we will examine here is that of unification. Unification is the idea that different phenomena are governed by a single—higher-level—theory instead of a theory for each phenomena. There is no real reason to believe that this is true generally, and this is one difficulty with practical application. Another difficulty is that all of our equations are, to one degree or another, an approximation of reality. So the fact that equations in different fields look alike is another way of saying that the approximations are similar. Does that mean the phenomena are also similar? Sometimes. Isaac Newton unified gravity at the surface of the Earth and gravity away from the Earth. James Maxwell unified electricity, magnetism, and light. Abdus Salam, Sheldon Glashow and Steven Weinberg unified electromagnetism and the weak nuclear force. The work of unifying electroweak theory with the strong interaction force is a work in progress. Even less success has been made in unifying gravity.