Laplace's Demon

However, all of this detailed understanding still reaches back to the deterministic Newtonian worldview. By the late 18th century, physical science had become thoroughly divorced from religion and determinism prevailed. In 1814, Laplace characterized the nature of a deterministic universe but without the possibility of free will [326]:

> *We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.*
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Such a hypothetical intelligence that can know all the forces upon it and predict the future has come to be known as *Laplace's Demon* [327]. This was the view taken into the late 18th and early 19th centuries and also involved extending the deterministic Newtonian picture from particles to include a new type of quantity, the concept of *field*. Laplace's *Mécanique Céleste* (1799-1825) included a reformulation of Newtonian mechanics in terms of a field, a quantity in which every point of space is assigned a magnitude and direction representing the acceleration produced by all the surrounding masses. This facilitated computation involving multiple bodies such as the 1846 prediction by John Couch Adams (1819-1892) and Jean-Joseph Leverrier (1811-1877) of the existence of the planet Neptune from irregularities found in the orbit of Uranus. The field concept played a further crucial role in the understanding of electricity, magnetism, and light by Faraday and Maxwell to profound effect, however, still under the influence of Newtonian determinism.

The determinism of Laplace's Demon stems from Newton's second law of motion and the existence and uniqueness theorems for solutions of the corresponding simultaneous differential equations of second order for which initial values of the dependent variables and their first derivatives are known at an initial time. However, exceptions to the uniqueness theorems were known at least since the work of Poisson at the beginning of the 19th century. In the 1870s, Boussinesq searched for exceptions to Laplace's Demon by way of singular solutions of certain classes of differential equations that have multiple solutions for certain initial conditions [328]. Later researchers focused on singular solutions in systems in which the force on a particle fails to satisfy a local Lipschitz continuity condition [329], which is known to be a sufficient condition for uniqueness. A simple example is *Norton's Dome,* the motion of a mass initially balanced at the summit of a symmetrical dome which has multiple solutions for the same initial conditions [330]. However, such exceptions did not make much impact on researchers. The success of deterministic Newtonian descriptions of the universe was so extensive and convincing that conditions guaranteeing existence and uniqueness of solutions were viewed as the essence of a good physical theory. As always, *nothing succeeds like success* [331].

Even if we know that a unique solution exists, predictions often require that we know the initial conditions with a particular accuracy. Laplace's Demon in some cases must be able to make its initial measurements with arbitrary accuracy. This is particularly true for *deterministically chaotic* systems, after Poincaré's discovery in the 1890s of the possibility of instabilities of celestial bodies whose long-term dynamics is exponentially sensitive to the initial conditions. Laplace's Demon was a precursor of many developments that explore whether there are limits on various aspects of knowledge. Even if Laplace's Demon knows the initial conditions to arbitrary accuracy, prediction may even be computationally undecidable or intractable and require computational power beyond that of any deterministic algorithm as was demonstrated later in the 20th century [332] [333]. Such behavior can be exhibited for example by *Turing machines* [334], idealized universal computers that use predefined rules to determine a result from a set of input variables. An intriguing property of Turing machines is the famous *Halting Theorem*: configurations exist for which it cannot be known *a priori* whether the machine will give a result and stop computing. As a consequence, the long-time behavior of Turing machines is completely unpredictable [335]. In a clockwork universe, the state of a system at an initial time completely determines the state at a later time. However, the *state* in classical mechanics becomes identified with the *measurement-outcome,* and these two concepts are very different in quantum theory where complementarity disrupts the identification of measurement and state. That determinism and causality are logically independent notions was noted by Bertrand Russell [336] and the distinction later became important with the emergence of quantum theory. There are counter examples of theories which are causal and nondeterministic as well as examples which are deterministic but non-causal [337]. Quantum physics is a probabilistic theory that is causal but not deterministic. Other limits on knowledge include restrictions on information transmission via the constancy of the speed of light within Einstein's Special Relativity, Heisenberg's uncertainty principle of quantum mechanics, and the restrictions imposed by the existence of quantum entanglement leading to a variety of *no-hidden-variable* theorems that distinguish classical and quantum phenomena. A continuing question throughout the 20th and 21st centuries has been how these various limits relate to each other. As physics expanded its horizons, the clock in any clockwork universe was no longer assembled from merely cogs and gears.

Maxwell's equations had carried the determinism of Newton over into the realm of electromagnetism. However, a decade prior to Poincaré's studies of chaos, Maxwell questioned how free will enters into nature. In 1873, he gave a talk entitled, "Does the progress of Physical Science tend to give any advantage to the opinion of Necessity (or Determinism) over that of Contingency of Events and the Freedom of the Will?," in which he delineated these distinctions [338]:

> *There are other classes of phenomena which are more complicated, and in which cases of instability may occur, the number of such cases increasing, in an exceedingly rapid manner, as the number of variables increases....In all such cases there is one common circumstance,—the system has a quantity of potential energy, which is capable of being transformed into motion, but which cannot begin to be so transformed till the system has reached a certain configuration…For example, the rock loosed by frost and balanced on a singular point of the mountain-side, the little spark which kindles the great forest, the little word which sets the world a fighting, the little scruple which prevents a man from doing his will, the little spore which blights all the potatoes, the little gemmule which makes us philosophers or idiots. Every existence above a certain rank has its singular points.*
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> *If, therefore, those cultivators of physical science…are led in pursuit of the arcana of science to the study of the singularities and instabilities, rather than the continuities and stabilities of things, the promotion of natural knowledge may tend to remove that prejudice in favour of determinism which seems to arise from assuming that the physical science of the future is a magnified image of that of the past.*

Maxwell emphasizes that there are phenomena which do not easily fit into the familiar deterministic framework and suggests that understanding of the physics of nondeterminism may arise from study of the physics associated with singularities and instabilities. He gave this talk shortly after he had devised his thought experiment for violating the Second Law of Thermodynamics in terms of yet another type of Demon, an entity, perhaps with free will, who could sort fast and slow molecules, which has come to be known as *Maxwell's Demon*. As will be discussed in the section *Irreversibility versus Demon,* this was yet another piece of the puzzle determining the meaning of measurement. That there may be exceptions to determinism was acknowledged occasionally and mostly in private or within small circles, but the applications of science toward the end of the 19th century almost exclusively embraced physical determinism. Any exceptions were in the use of statistical methods which were viewed as representing ignorance of underlying deterministic phenomena. But ideas of nondeterminism did drift in the background, at least in the minds of the more deductive thinkers.

As a student at the ETH Zurich around 1900, Einstein had been profoundly impressed by the ability of mechanics to provide explanations in areas that apparently had nothing to do with mechanics, for instance the mechanical theory of light, the kinetic theory of gases, and the deduction of the laws of thermodynamics from the statistical theory of classical mechanics [339, p. 18]. From the time of Newton until the close of the 19th century, the prevalent view among physicists was that mechanical concepts ultimately would suffice to explain all physical phenomena. Newtonian mechanics was so widespread and familiar in the 19th century that mechanical analogues of electromagnetic effects in terms of gears, idler wheels, and vortices were commonly devised to better understand and illustrate these phenomena. In 1863, Maxwell actually used a mechanical model as a guide to conclude that the vacuum displacement current must be added to the electromagnetic equations, which was the crucial element allowing him to derive the existence of electromagnetic waves in empty space moving at the speed of light [340, p. 356], Figure 5.5. He used this model to arrive at his Proposition 14, which modifies the equations for electric currents for the effect due to the elasticity of the medium by adding the displacement current $\dot{E}$ to Ampère's Law: $\nabla \times H = 4\pi j + \dot{E}$ [341]. Based on this result, Maxwell concluded that there should be electromagnetic waves: "We can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena." [342] Maxwell emphasized that any mechanical aides should be regarded as scaffolding to be taken down after achieving understanding, leaving the electromagnetic fields as the only reality. Whereas in Newton's formulation of the theory of gravitation the interaction between masses occurred instantly at a distance, we now know that the phenomena of electromagnetism have the subtlety that signals between charges proceeding at the speed of light, and this is implemented by waves of the electromagnetic field. However, those investigating electromagnetism in the late 19th century initially took

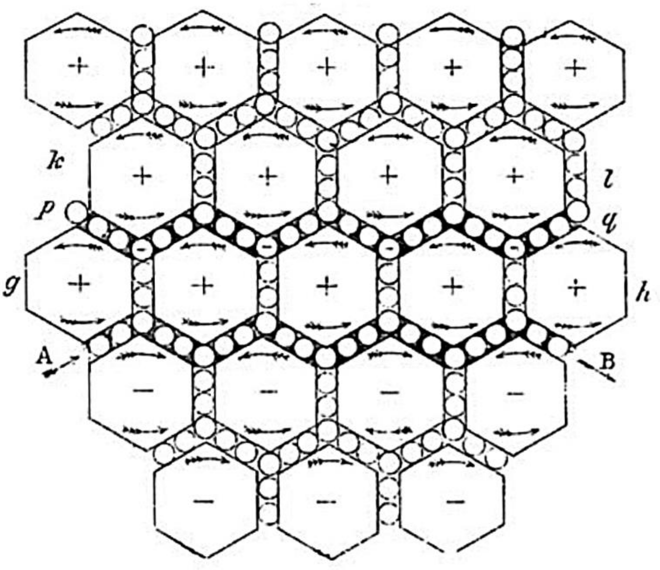

Figure 5.5: James Clerk Maxwell's mechanical model of gears and idler wheels for propagation of light through the luminerferous ether.

the view that electrical signals also acted instantly at a distance similar to Newtonian mechanics.