Lecture I.
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Extremely Complex Problems
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Materials science differs from the pure subjects in that it attempts problems at the level of complexity that is posed, rather than by simplification to study a narrow aspect. This raises challenges that usually involve interdisciplinary skills and myriads of non-linearly interacting variables. A second distinction is that there is a genuine yearning to validate predictions.

In this lecture I will introduce the method of neural networks within a Bayesian framework, a method that is a form of mathematical modelling that can help resolve complexity whilst striving for broader solutions. I will demonstrate that the method permits the discovery of new phenomena, and the quantitative design of new materials with a minimum use of resources. At the same time, it introduces a culture in which both noise and modelling uncertainties are considered in order to realize the value and limitations of the mathematical approach.

Some recent successes in the design of new materials include the _TRIP steel, a welding alloy that cancels the development of residual stress, and a nickel alloy that is cheap enough to serve in ultracritical steam driven power plant.
In ordinary life, we take it for granted that when sugar is added to tea, it will form a solution. In academia, we understand solid solutions that form by mixing elements in the liquid state followed by solidification. Less well understood is the process where solid particles of different composition are mixed together by mechanical alloying until they form an intimate solution that can be probed on an atomic level. In this lecture, I address this issue from the point of view of materials destined for fusion reactors or where they must resist severe oxidation and creep. Some discoveries are made in the process, that defy intuition and resolve some long-standing problems in thermodynamics and nucleation. Here goes.

Normal thermodynamic theory for solutions begins with the mixing of component atoms. Many solutions are, however, prepared by mixing together lumps of the components, each of which might contain millions of identical atoms. We examine here the way in which a solution evolves from these large clusters of components, from a purely thermodynamic point of view. There are some interesting results including the prediction that solution formation by the mechanical alloying of solid components cannot occur unless there is a gain in coherency as the particles become small. The nature of the barrier to mechanical alloying is discovered. There is also the possibility of a metastable state prior to the achievement of full solution, when the component atoms prefer like neighbors.

This is a story about a most elegant structure created in steel, consisting of incredibly fine and slender crystals of ferrite permeating a matrix of austenite. The crystals are typically 20–40 nm in thickness and in the form of plates. There are so many of these crystals per unit of volume, that a material is created which has one of the highest density of interfaces known to man.

And all this can be achieved in samples which are large in all three dimensions, without the use of deformation or rapid heat treatment, and at a cost which in terms of weight or volume compares with that of bottled-water. There is no new manufacturing technology required, the fabrication of the steel is conventional. But the heat–treatment is far from conventional, involving periods of up to ten days at temperatures in the vicinity of 200°C. The end result is a hardness in excess of 700 HV, strength of the order of 2.5 GPa, uniform ductility in the range 7-27%, and toughness in the range 30–50 MPam1/2.

The choreography of atoms during the transformation of austenite into the crystals of bainitic–ferrite has a major role in determining the structure. I will describe how the material was discovered and the underlying phase transformations theory. Hundreds of tonnes of the material has been produced and utilised in a variety of specialised engineering applications such as shafts and armour. The new science associated with this material, including a remarkable new Fe-C phase diagram, will be described.