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Editor's Desk

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It is often said that distinct epochs of human civilization are associated with materials that were prevalent at the time. In terms of food, clothing, housing, tools, medicines, and weaponry, materials are extremely vital to humans. We have progressed from the stone age to bronze, iron, steel, polymer, composites, and silicon ages, with the last three occurring almost concurrently. In an illuminating article, Mike Ashby (*Materials—a brief history*, Philosophical Magazine Letters, Vol. 88, 2008) compiled important milestones in different ages and discussed the triggers for each age. While there were pioneering scientific (chemistry in particular) and engineering advances that triggered the development of new materials such as polymers and semiconductors, Ashby says that it was also political conflicts, wars, and the competitive drive of free markets that pushed the boundaries of materials space. Current drivers of new material development, many argue, are sustainability, energy, and climate change. As the first two have always been important, it is unclear if these are new. However, every now and then, a new school of thought develops and takes over the reins of progress for a short period of time. One such idea is that of size effects. Speculating on the next age of materials, Ashby included the *nano age* because preferred nano-scale arrangements of atoms and molecules give unprecedented material properties, which he says nature thrives on. Biomaterials that interact with living matter are yet to catch up with nature's craft.

Materials research has traditionally been a very experimental endeavor. You synthesize a material, test it, and analyze the results to understand it. Alongside, there have been tremendous developments in theoretical and computational approaches. Quantum mechanical techniques such as the density functional theory are used today to model material behavior and deduce the properties. However, despite the progress, materials researchers seem unsatisfied with admittedly slow and costly trial-and-error approach to discovering or engineering new materials. So, the idea of *Materials Genome* was conceived to expedite the new material development. The term *genome* is debatable in this context. Rather than conceptual resemblance, it is most likely linked to the openly shared data and analytics associated with it. The white paper prepared by the US National Science and Technology Council (*Materials Genome Initiative for Global Competitiveness*, June 2011) preempts any argument by stating at the outset that "*…the word genome, when applied in non-biological contexts, connotes a fundamental building block toward a larger purpose*".

There are many more building blocks for materials than the elements in the periodic table. The material properties can be modified by tuning the distinct phases of the material, their composition, crystallography, microstructure, crystalline defects, and so on. And then there is noise and uncertainty in materials processing that makes it harder to achieve the desired properties. Through centuries of investigation, much has been learned, and there is yet more to learn. Like other fields today, some materials researchers believe that artificial intelligence and machine learning can help them get new insights faster and better from enormous amounts of experimental and computational data that are being amassed.

Materials Informatics is perhaps a better way to describe data-driven materials discovery than the material genome. Alan Mackay, who advocates the age-old dialectic technique in probing generalized crystallography, sought the convergence of crystallography, material science, and biology (*Foundations of Chemistry*, 1: 43–56, 1999). The basic questions of where and how the information is stored and how it is processed in the case of inanimate materials are worthy of pursuit in looking for the *inorganic gene*. For researchers who share this view, self-assembly and self-organization remain elusive, leave alone self-replication. A crystal for them is not "*a structure giving a diffraction pattern with discrete points*"; rather it is "*a structure whose description is much smaller than the structure itself and carries information about the structure at the larger scales*." Krishna Rajan (Materials Informatics: The Materials "Gene" and Big Data, *Annu. Rev. Mater. Res.* 2015. 45:153–69) discussed this idea further and argued that statistical learning methods have the potential to weed though the Big Data of Materials Informatics and

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reveal design rules for predicting structure–property correlation. It is a quest for wisdom through knowledge. In this context, Julyan Cartwright and Alan Mackay (*Phil. Trans. R. Soc. A* (2012) 370, 2807–2822) quoted T. S. Eliot's lines from *Choruses from* "*The Rock*" (a commissioned pageant play written in 1934):

Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?

and added two lines of their own:

Where is the information we have lost in data?
Where are the data we have lost in noise?

While exercising caution, they also suggest "integrating information theory into a new science of shape beyond crystals". A worthy goal indeed. It could change the course of history of materials by defining a new age of inanimate materials that rival living materials.

Interestingly, Ashby dedicated his article on materials history to Manuel Amaral Fortes who had worked extensively on cork and published a book *Cortica* in Portuguese. Ashby says that the humble cork has "*a history longer than that of almost any other*". Incidentally, it was cork that prompted Robert Hooke to hypothesize that living matter is made up of cells. Cork is buoyant, impermeable, abundant, and widely used. It has nearly zero Poisson's ratio: it does not contract or stretch appreciably in orthogonal directions when pulled or pushed. More importantly, it has cellular microstructure comprising pentagonal or hexagonal chambers with trapped gas. The buoyant and shape-recovery properties of cork arise from its cellular structure. Ashby was probably shy to comment in his article on the *age of cellular materials*, a topic that he himself has extensively investigated. There is renewed interest today on this topic with the advent of additive manufacturing (3D printing) that enables making components of porous interior designed to one's fancy. A single material whose microstructure is arranged in bespoke topologies, shapes, and sizes can widen the effective material properties. Sometimes, these properties can be unusual such as negative Poisson's ratio, negative refractive index, and so on. Until now, these were called *metamaterials*, adding to the intrigue. When these can be printed with polymers, metals, ceramics, and biological cells using coming-of-age 3D and 4D printers, we are quick to give this field a new name: *architected materials*. Would this have become a definitive age when one looks back in the future? Whether it does or not, innovations in materials research continue unabated.

In this issue that celebrates 75 years of IISc's Department of Materials Engineering (the name changed from Metallurgy at about the 50th-year juncture, in keeping with the times), we get to read about important advances in many subtopics of materials with a focus on sustainability. The efforts of the guest editors, the authors, and the supporting staff are sincerely appreciated.

Publisher's Note

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