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Intelligent Materials

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SUMMARY

Intelligence is the ability to learn from experience, comprehend complex situations, make choices, adapt, and act purposefully. Are the reported intelligent materials really intelligent?

For thousands of years, materials are instrumental for the survival and well-being of human beings on planet Earth. Early materials used include stones, wood, bark, skin, bones, and hides for shelter, protection, and treatment of ailments. Historical trends of major material systems as shown in Figure 1A suggest that the materials innovation has been the preoccupation of humans around the world. The major categories of innovations have seen materials move from Stone Age primitive materials and virgin use through thermochemistry in the seventeenth century, followed by electrochemistry in the eighteenth to the periodic table era in the twentieth century. A lot has been discovered in between. Now, the polymers and ceramics, piezoelectric, magnetic, thermoelectric, and semiconducting materials seem not novel anymore. Many state-of-the-art devices and applications based on these materials are in use. However, these materials and their devices still lack many functionalities, such as self-control, adaptability, sustainability, and intelligence, which are necessary for the increasingly sophisticated modern ways of living. The next generation of materials innovations is reckoned to be fueled with intelligent and low-carbon materials. The low-carbon materials are described as materials with low embodied and operational carbon. In other words, they are less damaging to the Earth's biosphere and in turn to human health. Intelligent materials as elaborated below will be the development trend of materials in the future. It is conceivable that the future materials will be both intelligent and low-carbon.

Necessity catalyzes innovation, creativity, and change. Hence, various research organizations and governments are now investing extensively in intelligent materials research. Figures 1B and 1C illustrate the recent trend and emphasis of related scientific publications. But are the reported materials truly intelligent materials? In order to answer this question satisfactorily, it is necessary to establish the term "intelligent" more accurately. Hence, it is reasonable to build on well-established related terminology in the scientific literature "human intelligence" and "artificial intelligence (AI)." There are a multitude of definitions and descriptions of human intelligence. For the sake of this discussion, we define human intelligence as the mental ability to learn from experience, comprehend complex situations, make choices, adapt, and act purposefully. It is an intellectual power of humans endowed with self-awareness. Human intelligence gives humans the cognitive abilities to learn, form concepts, understand, and reason, including the capacities to recognize patterns, innovate, plan, solve problems, employ language to communicate, and to experience and think. In a nutshell, human intelligence is a measure of humans' ability to set and achieve goals in a wide range of situations.

On the other hand, AI can be defined as a system's ability to correctly interpret external data, learn from such data, and use those learnings to achieve specific goals and tasks through flexible adaptation. Advanced traits of AI are yet to be realized satisfactorily and these include reasoning, knowledge, planning, learning, communication, perception, and the ability to move and manipulate objects. In the 1950s, mathematician Alan M. Turing proposed the Turing AI test in order to determine whether a computer could think. In a simplified approach, it proceeded as follows: a remote human interrogator distinguished between a computer and a human subject based on their replies to various questions posed by the interrogator. The human interrogator did not see or hear the robot or human subject and used only text to communicate. By means of a series of such tests (within a certain time frame) a computer's success at "thinking" could be measured by the inability of the interrogator to distinguish between the computer and the human subject.

Given the above descriptions, an ideal intelligent material may be defined as a material that comprehends experiences, is self-aware, and responds purposefully. Therefore, intelligent materials should have the ability to be aware of external stimuli and learn from it to optimize response behaviors for achieving their choices or goals to the greatest extent via applications performance. From the nanoscopic

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https://doi.org/10.1016/j.matt.2020.07.003

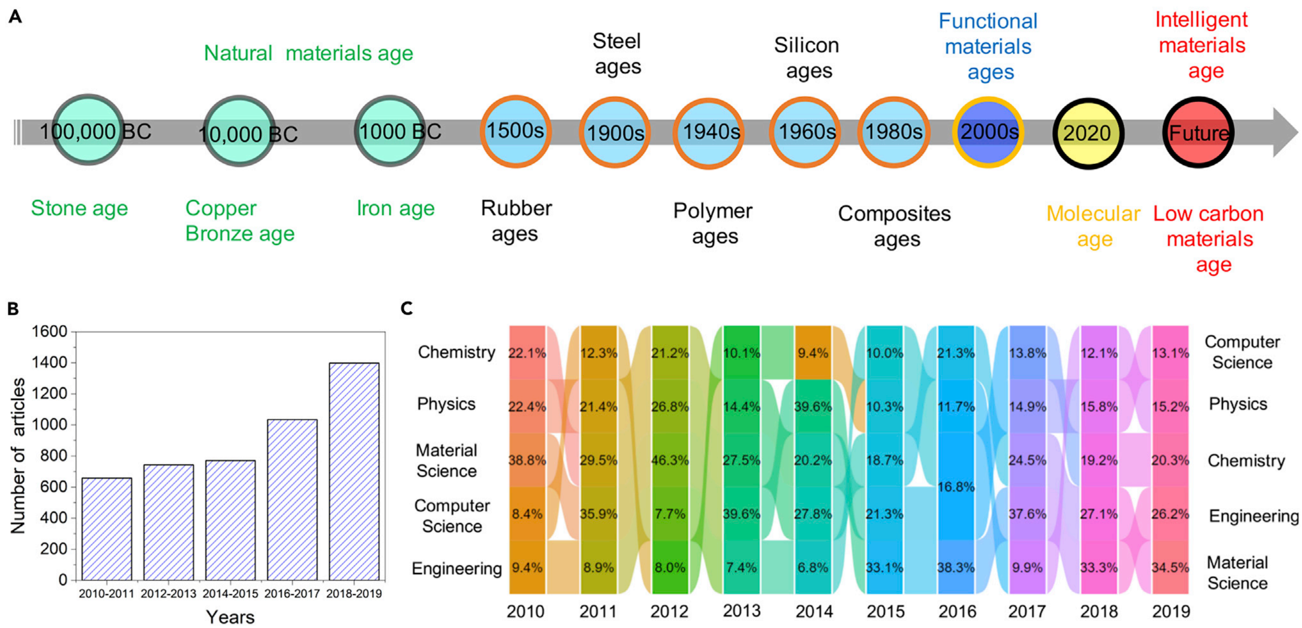

Figure 1. Major Progress in Materials

(A) The historical and emerging trend of engineering materials.

(B) Number of literature published per year on ''intelligent materials.''

(C) The interweaving of research directions on reported ''intelligent materials'' in terms of disciplines between 2010 and 2019.

level, the molecules or atoms of the material autonomously perform an active behavior to respond to the stimulus, such as the directional movement or aggregation of molecules or atoms. Therefore, the adaptive behaviors of material performance are reflected in the nano- as well as macroscopic level. The external stimulus can be electricity, light, heat, stress, strain, chemistry, nuclear radiation, etc. The goal is to achieve the optimization of a macro response of the material, including the deformation, electrical signal, color, etc. Such signals have successfully been reported in various materials, and this is what many researchers have been calling intelligence. Intelligence is more than simple responses as clearly detailed in the first sections. Therefore, after a response, there must be learning (from experience), comprehension of complex situations, decision making, adaptation, and purposeful action. In some of recent works, carbon nanotubes held in a 1D yarn structure were reported to be able to learn to be strong after initially subjecting them to mechanical stresses and strain.[1] However, this is only a crude example of intelligence that we are trying to write about here. Unlike AI, material science has no standardized test like the Turing Test to evaluate the intelligence of the material. We, therefore, propose a new non-linear scale or degrees of intelligence of a material to be judged in comparison to the intelligence of human neuronal networks and the definition of intelligent material.

In Figure 2, we examine the linear response of diverse materials purported as intelligent materials in the scientific literature and judge the intelligence according to their mechanisms and applications. Many ''intelligent materials'' in the existing literature and reports, including shape memory materials, piezoelectric materials, photovoltaic and thermoelectric materials, and so on are not intelligent enough but merely responsive. To further our claim, let's take an example of the shape memory behavior of shape memory materials such as Au-Cd/Ti-Ni alloys[2] and some polymers.[3] The transfer, aggregation, and rearrangement of their atoms caused by temperature change lead to thermoelasticity, martensite transformation, and its inversion in the materials. Because the materials' thermoelastic martensite transformation is passive and the internal material molecules do not take active actions against external stimuli to help shape change or recovery, these materials can be declared nonintelligent materials. Now let us suppose that a shape memory material is intelligent: what should it do? The material molecule can selectively undergo a martensitic transformation and determine the optimal deformation in some position according to the stimulus, so as to meet the application requirements for shape structure, deformation speed, and other features. Of course, there are some intelligent trends in shape memory materials for different environments.[4] These phenomena indicate that shape memory materials have the ability to show preliminary automatic responses to multiple stimuli, which

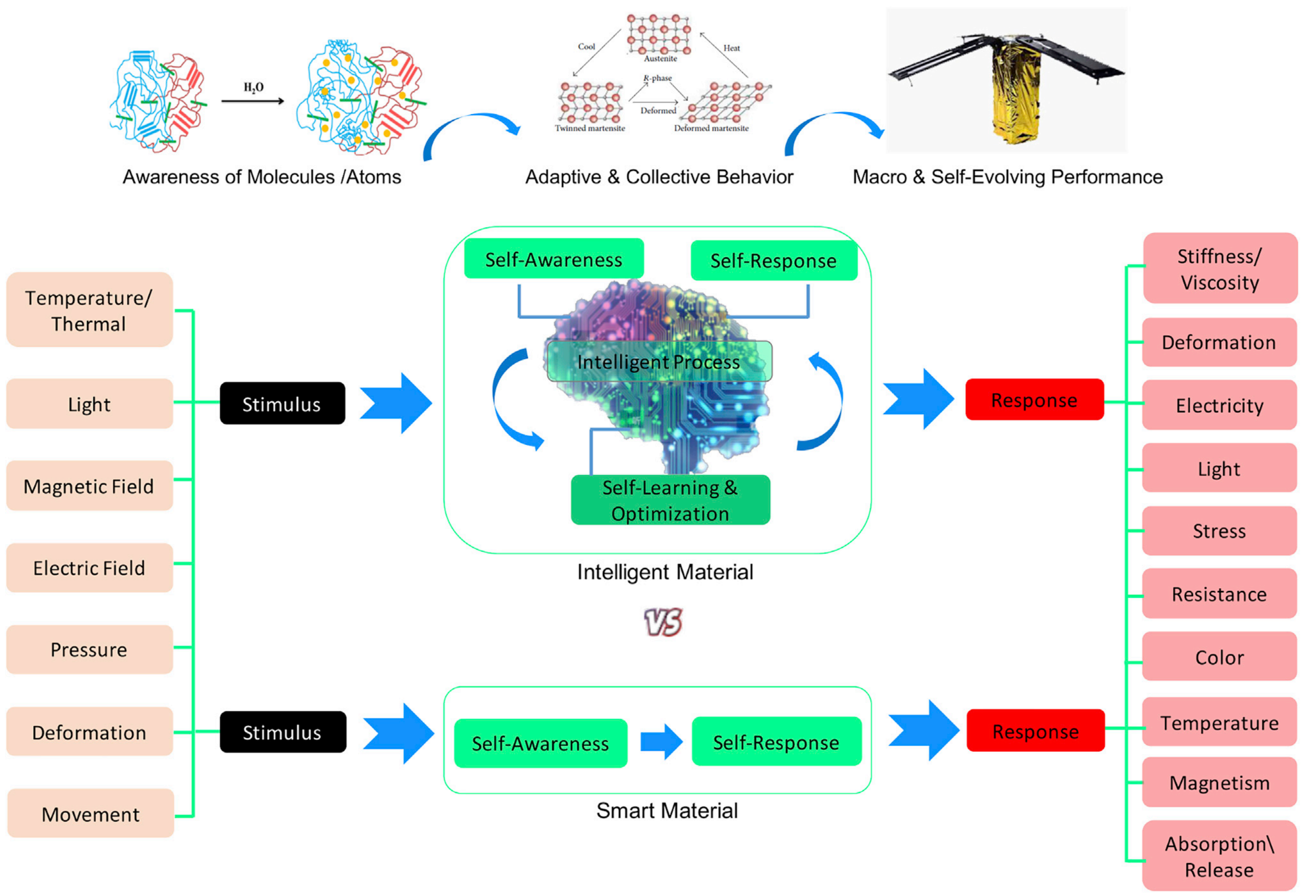

Figure 2. Intelligent Materials and Means to Interpret External and Internal Stimulus.
Intelligent materials show non-linear behavior whereas smart materials show linear behavior.

can be regarded as a basis for intelligent materials.

In other cases, the relative displacement of positive and negative ions in piezoelectric materials results in the macroscopic polarization of the crystal and the positive and negative charges at both ends of the crystal. From this basic principle, piezoelectric materials are not judged as truly intelligent materials. Although piezoelectric materials have been successfully used in micro sensors, mechanical energy harvesters, and micro drive devices as "intelligent" active materials, these are just applications based on the piezoelectric effect.[5] The molecules or atoms of the piezoelectric material do not move or gather spontaneously under pressure to regulate the charge behavior for promoting better piezoelectric effect. Photoelectric[6] and thermoelectric materials,[7] which convert light energy and heat energy into electrical energy based on the photovoltaic and Seebeck effect, respectively, also are not intelligent materials. If these materials have an ability to automatically adjust the width of the forbidden band and change the carrier concentration inside themselves relying on the intelligent characteristics of their own molecules or atoms, then they should be regarded as intelligent. The above materials in some literature are regarded as smart materials (which is a safer term). Smart materials have the ability to perceive and respond but not to self-optimize and improve, whereas intelligent materials perceive and analyze to summarize the experience and adapt to optimize the responsive performance. Scientists have recently made a new breakthrough in the exotic “fifth” state of matter (Bose–Einstein condensate) using the Cold Atomic Laboratory in Earth’s orbit, which is expected to unlock new properties of material matter.[8] At those extreme conditions, the matter begins to behave oddly: the atoms become one single entity, which show quantum properties. The emergence of new properties of materials and composite materials with multiple properties or effects, such as self-regulation, self-analysis, and self-response of the material atoms and molecules concerning external stimuli, will likely become the driving force for the development of intelligent materials.

In summary, we have attempted to redefine intelligent materials by utilizing definitions of human intelligence and AI. An intelligent material should be able to process external signals as well as internally generate signals in order to take actions that maximize its chance of successfully achieving its goals. Some existing materials reported in the literature were analyzed to help classify the level of intelligence from the complex of stimulus and responses. Realizing the development and large-scale application of intelligent materials in the emerging future is predicted to be a major revolution in material science, leading the leap-forward development of multiple disciplines in the fields of life, industry, deep sea, and aerospace. Thus, we encourage more researchers to invest efforts in intelligent materials that are truly intelligent.

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