What is a material?

If you are reading this article, you are probably a member of the Materials Research Society or at least are very interested in materials research. Consequently, I pose to you this burning question. What is a material?

My belief is that many people, if asked this question, would focus first on solids as materials. But what about liquids, gases, and plasmas? Dictionaries provide various definitions of "material" as a noun.[1] The definitions fall into three main categories: (1) matter, (2) textiles/cloth/fabric, and (3) information/data/ideas. The first definition seems circular to me, but has some aspects worth further consideration. The second is certainly relevant to our colleagues who study textiles, but is hardly complete. (Although, when I worked in the high fashion industry, many of the folks in that industry assumed that textiles, jewelry, and fragrances were the only materials worth considering.) The third group of definitions is not relevant to this discussion.

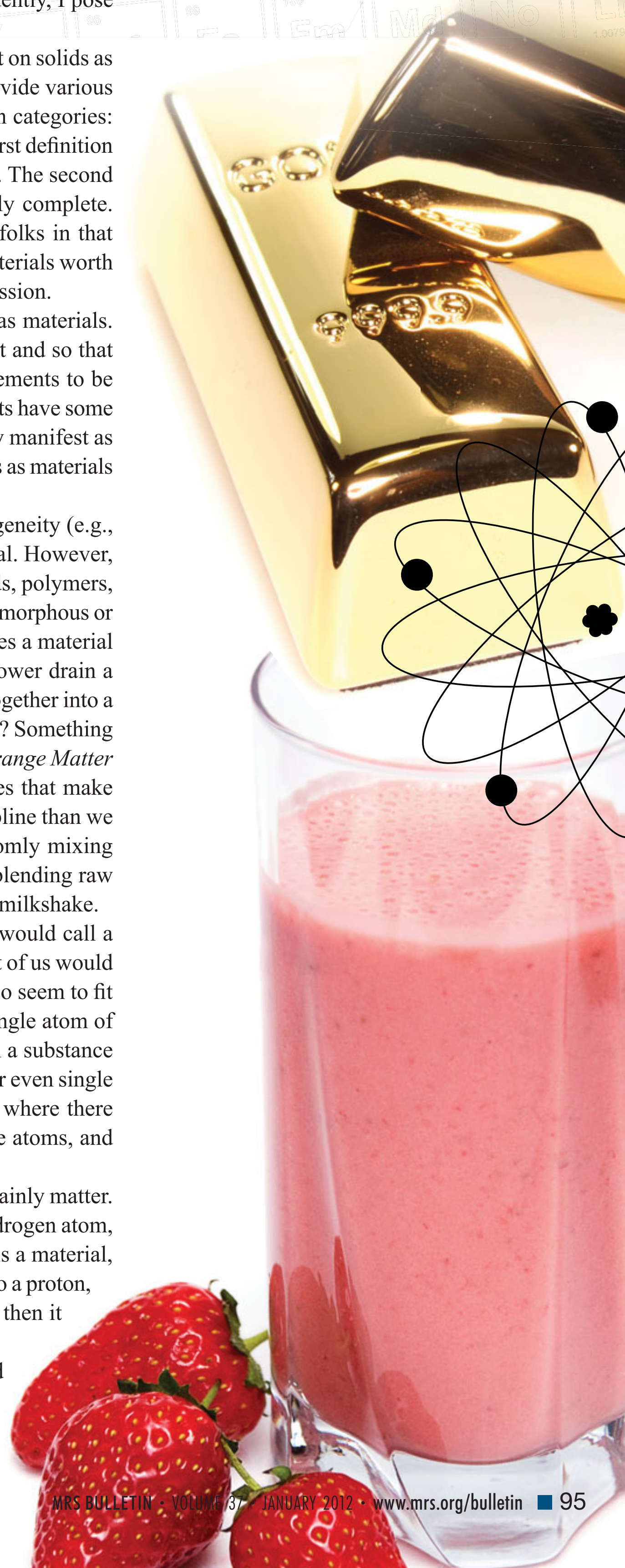
In some definitions, the elements of the periodic table are invoked as materials. The definition does not discuss the thermodynamic state of the element and so that leaves room for the liquids, gases, and plasmas as well as solids of elements to be considered materials. In fact, phase diagrams generally show that elements have some region of the pressure/temperature/volume phase diagram in which they manifest as solid, liquid, or gas. Consequently, it makes sense to consider all elements as materials without regard to their phase.

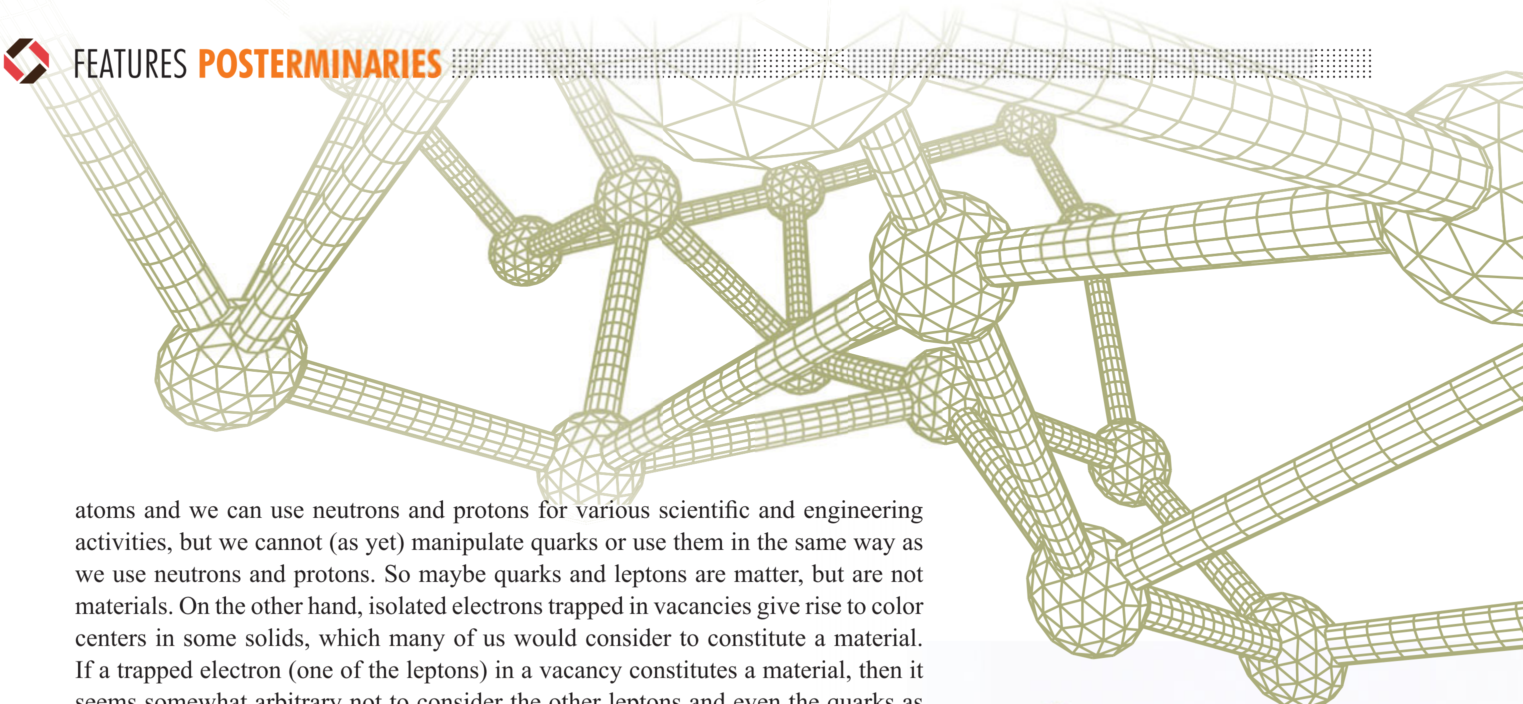
I also believe that some people would likely invoke issues of homogeneity (e.g., highly pure, crystalline silicon) in regard to the idea of what is a material. However, this limited perspective certainly leaves out mixtures, alloys, compounds, polymers, and other forms of heterogeneous materials. It also does not encompass amorphous or polycrystalline materials. It also seems to me the idea of what constitutes a material must have some element of reasonableness to it. Is the gunk in my shower drain a material? If I collect random articles from my trash bin and mash them together into a solid or even a gelatinous mélange, do those objects constitute a material? Something deep inside me rejects that, although it might fit into our discussion of *Strange Matter* (the MRS traveling science exhibition).[2] I know that there are mixtures that make good materials. Otherwise, metallurgy would be a much different discipline than we now know and alloy semiconductors would not exist. However, randomly mixing various things together does not make them a material any more than blending raw fish heads, cow brains, tripe, strawberries, and milk makes an enticing milkshake.

A collection of like atoms certainly seems to form an item that we would call a material. If I put enough gold atoms together to make a bar of gold, most of us would agree that this is a material. Nanoscale clusters of gold atoms would also seem to fit what we would call materials. However, what about two atoms? Is a single atom of gold a material? Is there any limit to the number of atoms below which a substance is not a material? We can certainly manipulate small numbers of atoms or even single atoms, organizing them into structures and moving them into regions where there are no similar atoms. There is utility in our ability to manipulate single atoms, and so maybe a single atom is a material.

Atoms, of course, are made of electrons and nucleons, which are certainly matter. But are electrons and nucleons materials? A proton is just an ionized hydrogen atom, so it seems somewhat arbitrary to believe that a single hydrogen atom is a material, but a proton is not. Bound neutrons are stable, but free neutrons decay into a proton, an electron, and an electron anti-neutrino.[3] So if a proton is a material, then it seems somewhat arbitrary not to consider a neutron as a material.

But, at least in the standard model of particle physics, neutrons and protons are made up of quarks. Now quarks are commonly considered as matter, but are they materials? We know how to manipulate





atoms and we can use neutrons and protons for various scientific and engineering activities, but we cannot (as yet) manipulate quarks or use them in the same way as we use neutrons and protons. So maybe quarks and leptons are matter, but are not materials. On the other hand, isolated electrons trapped in vacancies give rise to color centers in some solids, which many of us would consider to constitute a material. If a trapped electron (one of the leptons) in a vacancy constitutes a material, then it seems somewhat arbitrary not to consider the other leptons and even the quarks as materials.

At some point, we may be able to manipulate quarks and leptons in the same way that we manipulate atoms to alter materials properties. If so, then the Higgs particle and all forms of baryons and mesons become materials. Theorists have recently indicated that the spontaneous symmetry-breaking that results in ripples in graphene is similar to the physics of the Higgs particle. Could studies of graphene reveal the Higgs particle?[4] By extension (no pun intended), elementary strings with dimensions on the Planck scale become materials because they form the entities that we consider to be elementary particles.

Furthermore, what about vacuum? The common notion of a vacuum is space devoid of all matter, and yet even the purest of vacuums teems with quantum activity. Quantum field theory ascribes properties to the quantum vacuum based upon the emergence of virtual particles. These effects give rise to a range of phenomena including the quantum Casimir effect. Some studies have even attributed the existence of inertia to the quantum vacuum.[5] The quantum vacuum also possesses nonlinear optical properties.[6] Is the quantum vacuum a material? Cosmologists ascribe stress and strain tensors to space-time, and use language similar to solid-state researchers. Should we consider the quantum vacuum and all of space-time to be materials? Maybe all studies of elementary particles and cosmology are just other aspects of materials research.

I don't want to leave you with the perception that these questions are such burning philosophical issues that they torment me late at night. Nonetheless they are more interesting and more relevant than discussions of how many angels can dance on the head of a pin or whether or not famous celebrity couples (e.g., Brangelina) will break up soon. So somebody please tell me, what is a material?

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