

gen, and/or oxygen, are combined to form short covalent bonds. In the second, elements with very high densities of valence electrons are included to ensure that the materials resist being squeezed together.

The first approach gained favor in the late 1980s, when calculations suggested that the hypothetical compound C_3N_4 may be even less compressible than diamond (4). However, after years of experiments, further calculations indicated that even for the least compressible C_3N_4 structure, the shear modulus would only be 60% of the diamond value (5). New forms of carbon, including fullerenes and nanotubes, generated great excitement in the 1990s, when high-pressure processing produced very hard substances (1). However, these substances, which fall under the rubric of diamondlike coatings, can approach but never reach the hardness of diamond (6); furthermore, squeezing fullerenes and nanotubes is unlikely to be an inexpensive, practical synthetic route to diamondlike carbon. Three-dimensional boron-rich compounds, including B_4C , B_6O , their solid solutions, and B/C/N phases, are very hard materials that deserve continued study. However, this approach is unlikely to produce materials with hardnesses exceeding those of boron nitride/diamond solid solutions, which are intermediate in hardness between diamond and cubic boron nitride (1, 2, 7).

In the second approach, transition metals that have a high bulk modulus but low hardness are combined with small, covalent bond-forming atoms such as boron, carbon, nitrogen, and/or oxygen. In this way, a material that can maintain both volume and shape can be created. This idea has led to highly incompressible phases such as RuO_2 (8), WC, and Co_6W_6C (9). Unfortunately, these materials do not even approach the hardness of cubic boron nitride, owing to the partially ionic character of the Ru-O bond and the metallic nature of the W-W and Co-W interactions (3). Borides may be a better choice to achieve the required covalent bonding. Transition metal borides such as the tungsten borides WB_4 , WB_2 , and WB are promising (1, 2). Elements with a higher density of valence electrons (and thus high bulk modulus) such as rhenium, osmium, and iridium also have the potential to form very hard borides (10); mixed-metal borides could be even harder (see the figure).

Once the best combination of elements is found, hardness could be increased by controlling the underlying nanostructure. For example, if the motion of dislocations in a material is hindered, hardness can be increased. This phenomenon is well known to occur in an ultrafine-grained diamond called carbonado (11). More recently, nanoceramics with a grain size of ~10 nm have exhibited the same phenomenon (12). Superlattices of TiN/AlN or carbon nitride/TiN with a peri-

odicity of 6 to 8 nm also exhibit hardnesses two to three times as great as that of the bulk crystalline form of these materials (13, 14). In all these materials, the interfaces between the nanometer-scale components act as barriers to the movement of dislocations.

Despite all the research activity into synthesizing superhard materials, many opportunities remain unexplored. For example, the lightest element that could produce three-dimensional structures, beryllium, has been neglected, perhaps because it is toxic and may require specialized high-pressure equipment. Ternary phases of beryllium with other light elements—boron, carbon, nitrogen, and oxygen—could have exciting properties in their own right or in combination with high-valence electron density metals.

Despite their potential, new materials are unlikely to replace diamond altogether, because in addition to its hardness, diamond possesses many other amazing properties. It is the most incompressible material, has one of the highest indices of refraction, and has a room-temperature thermal conductivity five times as large as that of the best metals. The scientific challenge of finding a superhard

material that surpasses diamond in any of these properties will keep the field energized for years to come. Combining high hardness with other properties, such as chemical inertness and low-cost synthesis, could quickly yield practical benefits, for example, by providing a replacement for cubic boron nitride for cutting and polishing steel.

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10.1126/science.1109830

BIOMEDICINE

Hamiltonian Medicine: Why the Social Lives of Pathogens Matter

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Brushing your teeth is an experiment in social evolution. Brushing mixes bacteria that were previously surrounded by their clonemates with unrelated bacteria from another part of your mouth. This mixing reduces the relatedness among adjacent bacteria, which can in turn affect their behavior and, ultimately, whether they harm you. This argument is at the center of recent work suggesting that the social behavior of pathogens may be important in understanding disease virulence and antibiotic resistance.

Only some pathogens are dangerous. Understanding what causes virulent pathogens to emerge is a priority for both biologists and physicians (1). A key factor affecting the evolution of virulence is the number of different pathogen strains that infect a host (2–4). It was first thought that the

more strains there are in the host, the more virulent they should become. Frank (2) modeled the effect of multiple strains using Hamilton's kin selection theory (5). Originally developed to explain animal social behavior, kin selection theory revolutionized thinking by showing that related individuals cooperate with one another because of their shared genes (5). This approach can be applied to disease because multiple infections reduce relatedness among pathogens; kin selection then predicts that multiple infections should also decrease cooperation. The pathogens in Frank's model were not cooperating in a truly social sense but simply were solving the problem of how quickly to divide and reproduce. Frank predicted that low relatedness would make strains divide rapidly in competition, which would harm the host and increase virulence (2). Despite the elegant theory, many pathogens refused to cooperate with predictions. Studies on viral, bacterial, and plasmodial diseases found that mixed infection often favors the less virulent strain, showing that, contrary to Frank's theory, reduced relatedness often reduces virulence (3, 4, 6).

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