As they learn to speak, children often use words that they have already learned to name new objects, in a process called word meaning extension.

at three different scales: within children, within languages, and between languages.

Brochhagen *et al.* investigated how pairs of words found in these datasets are predicted by four types of knowledge: associativity (whether the words are semantically similar), visual similarity (e.g., a computer mouse is more similar to a rodent than an ice cream), taxonomic similarity (e.g., a mouse is closer to a cat than an ice cream), and affective similarity (e.g., ice creams are associated with happiness, mice less so). In all three datasets, the biggest driver of word pairing was associativity, followed by taxonomic and then visual similarity.

The authors found that taking a model trained on one dataset and applying it to another dataset explained word pairings in the second dataset almost as well as in the first. This suggests that there is a shared foundation underlying word meanings. Brochhagen *et al.* argue that this commonality is not an outcome of childhood errors becoming adulthood norms. Instead, they argue that there is an underlying common foundation—linguistic creativity. That is, both children and adults use their rich knowledge of the world and the objects in it to label new entities on the basis of their similarity to things they already know. It is this creativity that could cause the patterns of word meaning extension during childhood development (ontogeny) to recapitulate those in language evolution (phylogeny).

The analysis of Brochhagen *et al.* adds to recent studies showing that small-scale processes can have a substantial effect on language at a larger scale. For example, words that are more common (*4*) or have grammatical features that are more abstract (*5*) in daily speech tend to be those that evolve more slowly in the long term. Similarly, evidence indicates that low-level cognitive biases, such as a preference for interpreting noun phrases as the agent of a sentence, may have shaped the global patterns of language diversity (*6*).

Taken together, these findings have important implications for investigating language. The influences of linguistic creativity, usage, and cognition on language change are operating at a small scale—for example, within the brain or within a community with a common language—but accumulate to generate large-scale global patterns of linguistic diversity between languages and over time. Therefore, a theory of language change and evolution is needed that links the processes operating within individuals over milliseconds to those operating as children learn language and to those operating within and between communities over centuries.

This task will not be easy. Complex adaptive systems such as language require complex adaptive explanations operating at different scales (*7*). There are some promising signs that linguistics is heading toward this more-comprehensive framework. For example, there are an increasing number of theoretical attempts to connect processes across timescales (*8*). Researchers are interrogating whether language evolution conforms to predictions from general evolutionary theory or whether new theoretical constructs are required (*9*). Others have suggested experiments to test these predictions (*10*). In addition, there are an increasing number of large databases of primary language data from across the globe that enable researchers to ask questions about language change across multiple timescales (*1*, *11*). Linguistics as a whole is also undergoing a shift toward the use of more-robust quantitative methods (*12*), which will enable the application of powerful analytical tools to these data.

Combining these tools, data, and ideas will connect the processes causing change at different timescales and enable the identification of key causal pathways that have shaped humanity's linguistic diversity over time and across the globe. There are many exciting topics to explore in this space. For example, how do cognitive biases affect learning of the different languages found around the world? It will also be interesting to ask how learning interacts with language systems that are configured in different ways and how repeated pathways like grammaticalization (by which words representing objects and actions become grammatical markers) are affected by language acquisition and evolution. Quantifying sociolinguistic awareness of linguistic systems across languages and evaluating how these interact with the formation of social groups would also be an interesting area for future research. ■

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FRACTURE MECHANICS

Cracks break the sound barrier

Experiments show that tensile cracks can travel above the speed of sound

By **Michael Marder**

Cracks at scales too small to see permeate most solid objects, and they are dangerous when they grow and rip things apart. Thus, the study of crack dynamics is an important part of fracture mechanics—the discipline that explains the stress that cracked materials can sustain before they give way. This understanding is essential for applications ranging from airplane safety to earthquake detection and prediction. For many decades, there has been a consensus on the speed limit to crack propagation in a body pulled apart in tension. The limit is the speed at which sound travels across a free surface, called the Rayleigh wave speed. On page 415 of this issue, Wang *et al.* (*1*) report that the Rayleigh wave speed is not the limit after all; cracks can travel at the speed of sound and beyond.

Cracks have long been easiest to understand when studied through a combination of experiments in model materials and mathematical analysis. An early study of this type, in 1921, involved cracks in glass (*2*). It showed that the motion of a crack involves the interplay of two factors. When a crack extends, it relieves stress and recovers stored elastic potential energy. However, energy must be spent to pull atoms apart and rupture the material. A solid under stress is said to reach the Griffith point when these two factors exactly balance; if more stress is applied, the extra energy induces the crack movement. But how fast can the crack travel? A precise calculation of crack dynamics was achieved 30 years later, in 1951 (*3*), through an exact solution for a moving crack described as a sum of surface waves. It stands to reason that the speed of crack propagation is limited by the fastest surface wave. The solutions to the crack dynamics equation become singular;

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that is, they take infinite values as the crack approaches this speed, which corresponds to the Rayleigh wave speed (*4*).

According to current understanding (*5*, *6*), the limit of crack speed propagation is explained as a consequence of energy transport. The linear elastic theory of dynamic fracture states that one can draw a loop around the tip of a moving crack and compute the energy passing through the loop. When the crack tip reaches the Rayleigh wave speed, the energy expression approaches infinity; past the Rayleigh wave speed it becomes negative, and then at slightly higher speeds it becomes imaginary. Negative energy from a crack would make perpetual motion possible, and imaginary energy makes no sense; these are both violations of the laws of physics, so such cracks were assumed to be impossible.

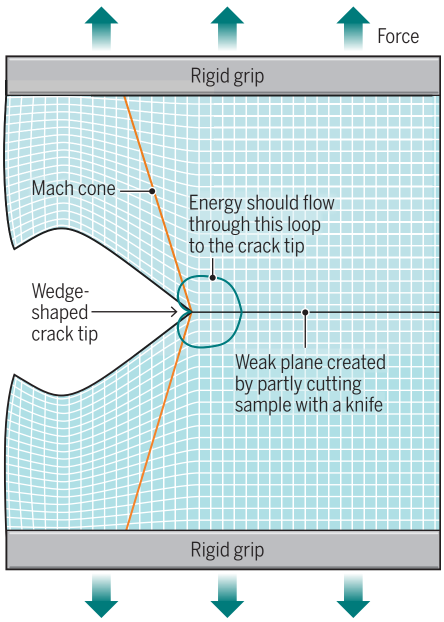
An exception to this assumption has been known for some time. It was demonstrated in 1976 (*7*) that when cracks are driven in shear (the forces driving the crack are parallel to the crack), there is a special velocity above the Rayleigh wave speed at which energy expressions become finite again. Some researchers (*8*) found supersonic cracks of this type in the lab, and others obtained them in simulations (*9*). Earthquakes can be cracks of this type too, which explains field observations of supersonic earthquakes.

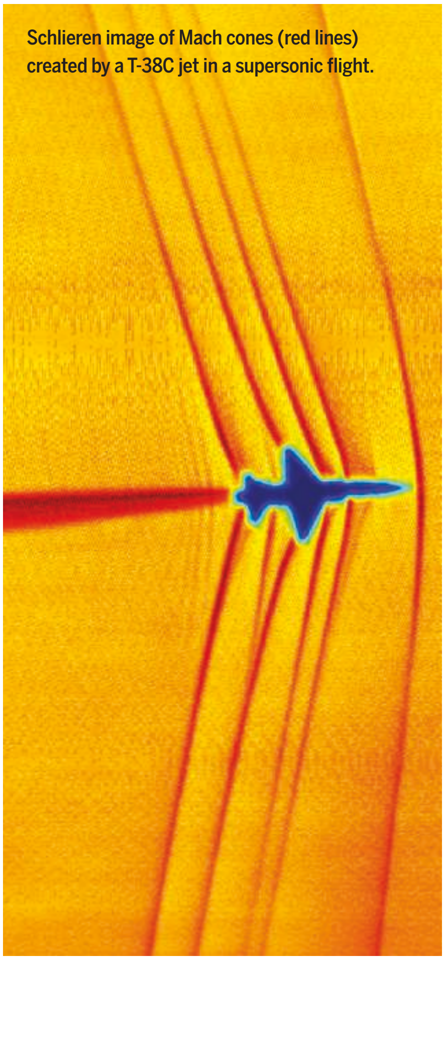
Thus, it was puzzling when cracks faster than the Rayleigh wave speed were observed in experiments carried out on rubber under tension (*10*). This was the scenario that the case of imaginary energies was supposed to forbid. One explanation put forward to resolve the difficulty was that near the tip of the crack, the speed of sound increases (*11*). Another possible explanation came from the dynamic theory for cracks in crystalline lattices, which found that once the discrete atomic nature of solids is treated explicitly in fracture theory, cracks can become supersonic without needing any increase in wave speed (*12*–*14*). But these findings failed to create a consensus that supersonic cracks under tension exist. Perhaps there was something peculiar about rubber, or the elastic theory that describes rubber, or lattice models. This is where community consensus rested for many years.

Now, Wang *et al.* have conducted laboratory experiments in a model brittle material, a polymer gel, where sound speeds are low and cracks are easy to follow. They carefully studied subsonic cracks in their samples and showed that the cracks obey in all detail predictions of the linear elastic theory of dynamic fracture. Then they pull harder and harder on the material and the

Supersonic crack in a lattice

In the linear elastic theory of dynamic fracture, cracks have rounded tips and move because energy flows into their tips. Supersonic cracks, driven by pulling hard on materials weakened along a plane, look different, with a wedge-like crack tip and Mach cones.





Schlieren image of Mach cones (red lines) created by a T-38C jet in a supersonic flight.

cracks accelerate, reaching and surpassing the Rayleigh wave speed.

A polymer gel is far from a regular crystalline lattice. Nevertheless, the experiments of Wang *et al.* act in many respects like supersonic cracks in lattices. Both systems display wedge-shaped tips surrounded by Mach cones, which refer to the shock waves that form around all supersonic objects, including aircraft, where the shocks create sonic booms (see the figure). Both in theory and in Wang's experiments, the speed of crack propagation depends on how much material in front of the crack has been stretched, rather than on how much energy is stored ahead of the crack as in the linear elastic theory of dynamic fracture. The polymer gel experiment shows no signs of rising wave speeds near the tip as proposed previously (*11*).

Thus, it appears there is a new domain of crack motion conventionally thought until now not to exist, where cracks under tension travel faster than the speed of sound. A necessary condition for such cracks to exist is that the tip must remain stable at high speeds—that is, the tip must keep from splitting, swerving, branching, or blunting. The new experiments by Wang *et al.* stabilize crack tips by weakening the plane along which the cracks travel. However, many questions about supersonic cracks are not resolved. It is not certain whether they can exist in all materials, or just special ones, and which materials' properties would need to be present. These are just some of the problems to solve next. ■

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