# Decoding the Chaos of Breakup

**A new principle underlying the physics of fragmentation explains why fragment sizes follow a specific, universal distribution.**

By **Ferenc Kun**

When a solid object shatters or a liquid drop disintegrates, predicting the outcome seems at first hopelessly difficult. In solids, cracks branch, merge, and arrest in unforeseeable ways; in liquids, jets and films stretch and rupture through complex instabilities. Yet, despite this apparent chaos, a surprisingly simple rule applies to the produced fragments, whether they are grains of rock, droplets from a bursting bubble, or splinters of glass (Fig. **1**). Namely, their size distribution follows a power law. The recurrence of this form across vastly different materials and energy scales hints at an underlying organizing principle. Now Emmanuel Villermaux at Aix-Marseille University in France and the University Institute of France has proposed such a principle [**1**]. It shows that the statistical regularities of fragmentation can emerge from a combination of maximum randomness and kinematic constraints, without reference to any specific microscopic mechanism. The principle could help scientists determine how different physical processes influence fragment-size distributions in industrial, geophysical, and astrophysical settings.

**Figure 1:** The shattering of glass is an archetypal fragmentation process.
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Fragmentation processes have long fascinated physicists because they combine elements of geometry, dynamics, and disorder [**2**–**4**]. Numerous physical models have been proposed to explain the observed power-law size distributions. Many rely on microscopic mechanisms, such as the formation and propagation of cracks in heterogeneous materials, the branching and merging of these cracks, and the coalescence of damage zones [**3**]. Others invoke periodic stress patterns or hierarchical breaking, which under controlled conditions can lead to predictable fragment sizes [**4**]. In a different spirit, statistical models have treated fragmentation as a kind of phase transition, in which the system evolves from a connected state to a dispersed state when the imparted energy exceeds a critical threshold. That approach captures certain scaling features but still depends on system-specific interactions and parameters [**5**, **6**]. Collectively, these physical models have successfully described heterogeneous brittle materials, but they are not general and depend on the details of crack dynamics.

Villermaux took a very different path. Rather than asking how fragments form, he asked which outcomes are statistically most probable, given minimal physical constraints. He assumed that the breakup proceeds under maximal randomness, analogous to the so-called molecular-chaos hypothesis in Boltzmann's kinetic theory of gases. Among all possible ways of breaking an object into pieces, the realized one is the most probable—that is, the one that maximizes entropy. However, this randomness is not unconstrained: The process must obey a global conservation law identified in fragmentation studies over the past decade [**7**]. According to that law, the average of the logarithm of fragment sizes is conserved during breakup.

Given this recipe of maximum entropy subject to conservation, Villermaux found that the familiar power-law size distribution naturally emerges. Moreover, the exponent of the power law is

determined by the dimensionality of the breaking object—a 1D rod, a 2D plate, or a 3D solid or droplet. Villermaux's predicted exponents of 1.3, 2.4, and 3.5 for 1D, 2D, and 3D systems, respectively, match a remarkable range of experimental and numerical results [**2**–**4**, **8**]. These results span from shattering glass rods and exploding ceramic tubes to bubbles and droplets in turbulent flows.

The simplicity and success of this approach are striking. The findings suggest that the statistical features of fragmentation might be dictated not by the microscopic details of cracks or instabilities but by how randomness is constrained by global kinematics. Such a perspective is reminiscent of the historical development of statistical mechanics, in which macroscopic regularities arise from probabilistic laws rather than detailed dynamics.

Villermaux went further by testing the limits of his framework. He examined cases in which the assumptions of brittleness or randomness break down. In ductile or viscoelastic materials, for example, cracks might heal before fully separating, suppressing the formation of small fragments. Accounting for this effect modified the power law into a slower decay, consistent with experiments on ductile plastic materials [**9**]. Similarly, when finite impact energy limited the total surface area that could be created, the size distribution developed an exponential cutoff at small scales—again, a feature widely observed in data. These refinements strengthen the case that the new framework not only captures the essential statistical structure of fragmentation but also accommodates deviations introduced by material- and system-specific mechanisms.

This work provides a unifying statistical foundation for a research area long dominated by case-specific models. It shows that the interplay of randomness and kinematic constraints can explain why fragment sizes follow power laws and why the exponents cluster around characteristic values. The approach also offers a way to incorporate more detailed physical effects through additional constraints—such as finite energy, healing, or interactions among fragments.

Looking ahead, one might wonder whether similar principles could explain other geometrical aspects of fragmentation—not only the statistics of fragment size but also of the shapes of the pieces. In Villermaux's formulation, fragments are treated as ideal Euclidean objects whose internal geometry plays no explicit role in the breakup. In reality, fragmentation produces polyhedral pieces that statistically evolve toward an average cubic shape, as demonstrated in previous work [**10**]. Developing a corresponding principle for shape selection, and perhaps linking it to the statistics of crack networks or to surface-area minimization under random strains, could be the next step toward a comprehensive statistical theory of fragmentation.

**Ferenc Kun:** Department of Theoretical Physics, University of Debrecen, Debrecen, Hungary

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