The Pattern of Necessity

Aaron Fagan, Senior Editor

Step into an autumn landscape, and it quickly becomes clear that nature has little regard for tidy rules. Leaves spiral unpredictably, pumpkins swell into odd asymmetries, and apples wrinkle and pucker around their stems. Yet engineers have long clung to the comforting principle that form follows function, as if everything were designed purely to serve its purpose without deviation. Harvard's L. Mahadevan, professor of applied mathematics, physics, and biology, reminds us that this is rarely the case. Through studies of crumpled paper, folding brains, termite architecture, and the trajectories of coins, he shows that what first appears chaotic often obeys a hidden logic—intricate, surprising, and unexpectedly beautiful.

Take the brain. As the cortex grows, it expands faster than the underlying tissue. The result? Compression, then folding. Those wrinkled ridges aren't arbitrary; they increase surface area for processing power. But the exact patterns of folds emerge from a balance of growth, physics, and constraints. The form isn't chosen; it's forced.

The involute tooth form tells a similar story. It isn't the product of aesthetic whim but of inevitability. Given the constraints of rotation, rolling contact, and load transfer, the involute emerges as the only workable solution. Much like the folds in a brain, its elegance is less about choice than about necessity.

Or consider termites. Individually, they are simple creatures. Collectively, they build towering mounds that regulate airflow, temperature, and carbon dioxide. No foreman termite draws up blueprints; instead, the mound grows through local feedback loops, with workers responding to humidity and pheromone cues. It's an example of what engineers' term *stigmergy*, where individuals coordinate not by talking but by leaving traces that guide the next action. Out of these simple interactions, grand patterns and complex structures emerge, as if the environment itself were the conductor of a silent orchestra. Function, in this case, doesn't dictate form from the top down, it emerges through interaction.

Sound familiar? A gear is never alone. Its performance depends not just on its tooth form but on assembly, lubrication, housing stiffness, and operating environment. Noise, vibration, and wear emerge not from the tooth itself but from the dance of components working in concert. Like termite mounds, gearboxes are systems where form and function co-evolve through feedback.

Mahadevan has even built robotic swarms inspired by termites and ants, machines that, following only simple rules, can construct surprisingly complex outcomes. In the gear industry, we're beginning to see a parallel: AI-driven optimization, where iterative algorithms tweak microgeometry, modify profiles, and adjust materials in search of performance gains. Instead of a master plan, better designs emerge from cycles of feedback and adjustment.

So, what's the lesson for engineers designing quieter, stronger, more reliable gears? Perhaps it's humility. In nature, there is rarely a single correct form. Systems adapt, evolve, and self-organize. Our gear teeth may be involutes out of necessity, but everything around them—their interactions, environments, and feedback loops—remains negotiable. Form and function rarely follow a simple order; like leaves twisting unpredictably in autumn, gears too find their shape through subtle adjustments, emerging over time from a quiet interplay of forces and feedback.