Therein, the ordinary rank-four elasticity tensor is replaced by up to nine tensors. In addition to displacements, these tensors describe how rotations and deformations of the material microstructure — which can be periodic, but need not be — are connected to forces and torques. The tensor elements also directly determine the characteristic length scale.

This mapping onto generalized effective-medium parameters has, for example, been performed for human bone[6], suggesting that the effects of non-scalability are important in everyday life. It could well be successful for the present experiments too. Otherwise, a devil's advocate might argue that the properties Coulais *et al.* have observed are not effective metamaterial properties but rather properties of a complex structure made out of an ordinary elastic constituent material.

The study also prompts one to ask what the upper limits for the characteristic length scale might be in practice for any kind of mechanical metamaterial. This question is relevant because it would be even more striking if one could realize experimentally significant deviations from scalability in metamaterials with hundreds or thousands of unit cells — instead of order ten — along any one direction.

Finally, one wonders whether the lattice constants of millimetre order probed in the study could be drastically miniaturized to the microscale. To laymen, such microstructured metamaterials[7–9] would no longer seem to be mere toy models, but rather widely appreciated as real-world materials. ❒

Muamer Kadic, Tobias Frenzel and Martin Wegener are at the Institute of Applied Physics and Institute of Nanotechnology at Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany. M.K. is also at the Institut FEMTO-ST, CNRS at the Université de Bourgogne Franche-Comté, 25000 Besançon, France.
e-mail: muamer.kadic@gmail.com

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ECONOMIC COMPLEXITY

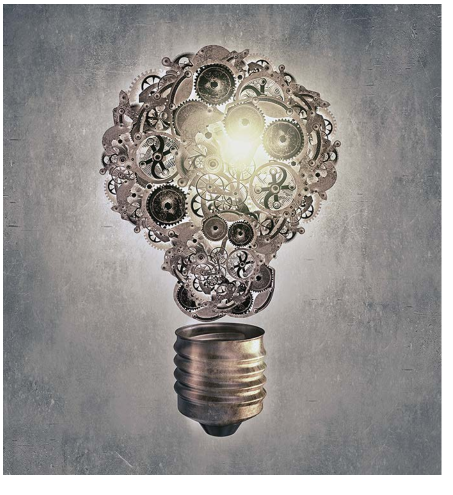
From useless to keystone

Technological innovation seems to be dominated by chance. But a new mathematical analysis suggests we might be able to anticipate when seemingly useless technologies become keystones of more complex environments.

César A. Hidalgo

Decades ago, when Norbert Wiener and Claude Shannon were fighting to define the field of artificial intelligence (AI), AI wasn't very useful. Wiener's flavour of AI, cybernetics, focused on feedbacks and control, and interested the army because it could be used to adjust the angle of machine guns firing projectiles from moving planes.

But much has changed since the times of Shannon and Wiener. In 2017, AI is the new centre of everything. It promises to make our garbage trucks, refrigerators, value chains and, maybe, even our governments smarter. But could we have foreseen the ubiquitous value of AI sixty years ago? Is it normal for relatively useless technologies to grow into keystone activities?


SERGEY NIVENS / ALAMY STOCK PHOTO

Writing in *Nature Communications*, Thomas Fink and co-authors[1] now demonstrate that the tale of AI should not surprise us. In their study, they break down the mathematics of innovation as a search process across components to show that the utility of a technological 'ingredient' changes in usefulness as the number of ingredients available in the world, and the complexity of the possible 'recipes', increases. Somehow counterintuitively, they find that some ingredients that start as relatively useless become some of the most useful as the world becomes more complex.

Consider two of their examples: the use of ingredients in cooking recipes and the use of software libraries in computing projects. When it comes to cooking, some ingredients, such as beef, are immediately useful (maybe with a bit of salt). Other ingredients, such as cayenne pepper, are useless by themselves, but very useful in a world with many ingredients and intricate recipes. But what works for cayenne also works for software. Redis, a database caching system, is used in few simple software projects, but it is central for multiple complex projects, where a swift interaction between back end and front end is required. In both kitchens and software development, ingredients that start as relatively useless can grow into some of the most useful, as pantries and software development projects grow increasingly complex.

Fink *et al.* build on a variety of literatures, including the recombinant growth literature in economics, the innovation literature in economic geography, and the more recent literature in economic complexity. These fields have pioneered the idea that innovation and economic growth are the result of a combinatorial process[2–6]. Much ink has been spilled in the formalization of models where economic activities are the combination of inputs, from the seminal growth models combining capital and labour[2], to the recent models predicting the economic activities that regions will enter in the future[6].

The main assumption behind all these models is basically the same: value comes from the complementarity of inputs. That's an obvious idea, since the value of a can opener only materializes in a world with cans. Yet, there are non-trivial implications that emerge from this simple idea. For instance, if value comes from input complementarities and the number of inputs in the world increases, the rate of growth of an economy will be limited not by the space of possibilities, but by the cost of searching for those that are useful[5].

The fact that value comes from complementarities tells us two important things about the industrial structure of regional economies. The first one is that the activities in which an economy will enter will be related to those present at a given location, since firms and regions only have an incentive to accumulate inputs that are complementary to those that they have available[6,7]. This is true not only for products[6] and industries[7,8], but also for patents[9] and research areas[10]. The second implication is that the mix of activities present in a relatively non-diverse location will be a subset of the mix of activities present in a relatively diverse location, since the more diverse location is likely to contain most of the combinations of inputs needed to enter the activities in the less diverse location, plus some more[4,11].

Fink *et al.* add to this literature by introducing another implication of input complementarity. This is the idea that, in a world where highly complementarity inputs are required mostly in complex economic activities, these inputs (or technologies) will start as useless, and will evolve into something useful only as other inputs become available.

We've seen that story play before. Beyond AI, consider steam engines: they were a mere curiosity for centuries. And when they were finally improved, they were used to pump water out of the dark and wet coal mines in the UK, and only later to power trains. Consider writing, an invention originally adopted by a few members of the elite, which is now a basic skill for almost every job.

But there is also something hopeful in Fink and colleagues' message. Everyone in the scientific community has heard the argument that science does not need to be too close to applications, as these usually come much after. This is an intuition that every scientist has, because they know how old some of the ideas they are using are, and also how limited the utility of these ideas may have been. When Adrien-Marie Legendre discovered his eponymous polynomials, he probably did not know that he was contributing to the understanding of the angular momentum of the hydrogen atom that emerged a century later. When Joseph Fourier developed his famous expansions, he probably did not realize that he was advancing the mathematics needed to compress images and audio on the Internet. When Warren McCulloch and Walter Pitts first wrote about neural networks, they probably did not imagine that they were starting a revolution in computer vision, autonomous vehicles and government surveillance.

The results of Fink *et al.* help formalize this intuition and narrow down the conditions when we expect this to happen. This adds to our understanding of innovation and also adds value to the growing literature on economic growth, geography and complexity. When put together, this literature helps us to understand a heretofore less-explored aspect of economics — the economics of creation, and not just that of transactions. ❐

César A. Hidalgo leads the Collective Learning Group at the MIT Media Lab, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: hidalgo@mit.edu

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