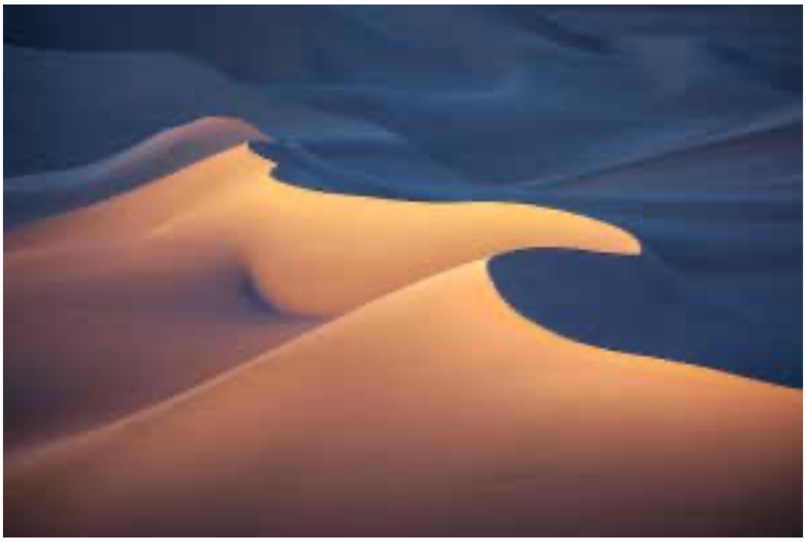
How are sand dunes formed and why do they even exist?

The strange, beautiful shapes that sand dunes form are a mystery. Now researchers are conducting huge desert experiments and using dune racetracks to figure it out



The Ibex Dunes in Death Valley, California, are stereotypical shape-shifting, wind-blown golden dunes

THE Israeli city of Ashdod has all the features found in a modern metropolis. Shopping malls, theatres, nightclubs, bars, plenty of good schools. But there is something else, too. Every weekend, at least in normal times, its citizens grab their buckets, spades and quad bikes and head for the city's most unexpected attraction: the biggest urban sandpit in the world.

Ashdod's Big Dune, up to 35 metres high and with the footprint of a dozen football pitches, dominates the city's largely undeveloped neighbourhood 14. One of the last remnants of the region's original coastal landscape, it isn't just a much-loved urban talking point, but also a dramatic example of a long-standing mystery. As bizarre as it sounds, scientists aren't sure how it got there – or indeed why any of the world's sand dunes exist.

On one level the answer to that question is obvious: the wind blows individual sand grains into piles. But exactly how and why dunes form in the way they do still eludes us. Now efforts to get to the bottom of this are taking on a new urgency, and not just because they could solve what Nathalie Vriend at the University of Cambridge explains is a "fundamental physics problem". As more human developments push into desert terrain and parts of the world grow drier due to climate change, the race is on to better predict the paths of shifting sands.

Think of sand dunes and the Sahara desert might spring first to mind, its endless expanse of golden sand in undulations of all shapes and sizes blown by the wind and shape-shifting constantly. There are of course many other dunes to behold – including one patch known as the Seven Coloured Earths in Mauritius, which has tones of red, orange, lilac and more thanks to the underlying geology. Dunes form underwater as well, and can even be found on other planets (see "Space dunes").

But those seas of differently sized dunes characteristic of the Sahara are especially puzzling. We know from comparing aerial photos that dunes migrate. Small ones travel quickly – up to 100 metres a year – and larger ones more slowly. If the dunes are moving around at different speeds, however, they ought to hit each other occasionally, at which point one of two things could happen. They could exchange material, in which case all the dunes would eventually be the same size. Or they could merge, which would produce bigger and bigger dunes – and ultimately one giant dune. The first big mystery of dunes is why neither of these things happen.

The second is how sand dunes grow to begin with. We see ripples in the sand a few centimetres high and we see small dunes about a metre high, but nothing in between. This leads some to say that dunes have a "forbidden wavelength". It is unclear how dunes overcome it, as they must surely do.

One of the first to look seriously at the way wind-blown sand dunes behaved was a British soldier and geologist called Ralph Bagnold. He learned first-hand about the difficulties sand dunes can present during his years leading expeditions across the deserts of Egypt and Libya in the 1930s. Bagnold was so curious about these mysterious transformations that he ultimately built a plywood wind tunnel in London to watch and photograph how different sized sand grains were blown and bumped along. He derived some of the first equations to explain these interactions. His 1941 book *The Physics of Blown Sand and Desert Dunes* was the go-to text for decades.

Modern sand dune experiments tend to take place on a grander scale, either on beaches or using vast, artificially flattened stretches of desert. Many occur in China, where developers are working to reclaim land from swathes of the inhospitable Taklamakan desert in order to build new homes and communities for its increasing population.

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On highways built across Taklamakan dune fields, engineers face a constant battle to stop blowing sand turning this new Silk Road into a silt road. "For the social and economic development of China, they have to find a way to deal with sand dunes," says Clément Narteau, a geophysicist at the Institute of Earth Physics of Paris in France.

The dunes don't give up their secrets easily. In 2007, Narteau, together with Lü Ping at the Chinese Academy of Sciences in Lanzhou, flattened an area the size of 16 football pitches in a remote part of the Tengger desert in Inner Mongolia, China. They wanted to track the very early stages of dune formation to see how they cross the forbidden wavelength. But when the researchers returned three months later to take their first measurements, they were too late. Sitting in the sand was a series of neat and repetitive dunes, each about 1 metre high. As the scientists wrote, no-doubt through gritted teeth, when they reported their results in 2014: "It is clear that the characterization of the early growth phase requires more frequent measurements, particularly at the beginning of the experiment."

There was excitement among dune researchers in 2018, however, when Klaus Kroy at the University of Leipzig in Germany and his colleagues spotted proto-dunes in the forbidden wavelength. It was the first time such formations, about 10 centimetres high, had been seen, and they received a suitably awesome name: megaripples. But megaripples only form in specific circumstances. Instead of being blown into shape, they emerge when larger sand grains roll off a dune and hit and disturb a surrounding smooth surface. So the broader mystery remained.

Meanwhile, the bulldozers had started up again in China. In 2013, Ping and Narteau's team flattened a smaller, 100 metres by 100 metres area of the Tengger desert. This time, they watched carefully from the start. "We used a laser scanner and we took many more topological measurements," says Narteau. He says these new results "completely solve the problem" of how dunes cross the forbidden wavelength, but they are still finalising the details to submit them to a scientific journal.

Those tantalising findings could cap a productive few months for sand scientists. Earlier this year, Vriend's team took a stride towards answering that other mystery of why sand dunes of different sizes can coexist. They did this by building a "dune racetrack", a ring-shaped tank in which miniature sand dunes can move. Rather than wait months and years for the dunes to shift with the wind, the researchers accelerated things by using pumped water to move the sand. The physics, Vriend says, is mostly the same.

The team found that dunes communicate with each other. When in the real world an upstream dune deflects air, it generates turbulent swirls that push a downstream dune away, even if it is larger and slower. "The front dune gets a kick from the back dune," says Vriend. This finally explains why dunes don't coalesce.

It is becoming increasingly important to understand such dynamics, Vriend says. "Dunes are becoming more and more prominent because of desertification and drying of our world."

In places like Morocco, rivers have dried up and exposed sandy sediment that is now blowing onto what was previously rich farmland. Towns and cities across the Sahel region of Africa, including Nouakchott, the capital of Mauritania, frequently have to dig buildings and roads out from encroaching dunes. "We really need to know how dunes move and how they behave to see if we can influence that behaviour," says Vriend.

Building walls won't do it. "That's the worst thing you can do," says Vriend. As the wind blows over the wall it creates a low-pressure wake that allows sand to deposit there. "So you end up with the object you're trying to protect actually being swamped with sand," she says. The best option is to model where dunes will go next and so make better decisions about where to build, or plant vegetation to stabilise a dune. Failing that, dunes may just have to be removed.

The shifting of dunes is a problem that city planners in Ashdod are wrestling with. The Big Dune is creeping towards built-up areas at up to 3 metres a year. "Having a dune in the middle of the town is a big problem," says Haim Tsoar, a geologist at Ben-Gurion University of the Negev, Israel. If they cannot find a way to manage the dune, eventually Tsoar wants bulldozers to move in and destroy it. Already the trampling of feet and grinding of quad bike tyres have denuded the sand of vegetation and ecological value, he points out. Without action, the Big Dune will overwhelm an area of new development known as the special neighbourhood.

Tsoar estimates it will be about 50 years before it reaches this part of the city and starts to engulf it. That leaves time to try to exploit new scientific insights and find an elegant solution to the shifting sands.