CAVEMEN IN SPACE

Underground caverns in our Solar System could serve as a means to explore other worlds – and safe enough to send humans

Reported by James Romero

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"The first thing that comes to my mind when I think of a cave is home," says Martin Gasser, a speleologist, or cave scientist, who along with his wife, geologist Christa Feucht, is a leading expert on the subterranean worlds below western Iceland. After two decades exploring the region, one cave has become the focus of their attention. Surtshellir is the longest in the country. Its mile of magma- and basalt-walled tunnels has been used as a hideout for bandits since the 10th century.

This infamy has come at a price. Over the centuries the spectacular stalagmites and stalactites have been damaged and stolen by souvenir hunters. Ordinarily such vandalism would dishearten a speleologist. Yet this was exactly what Gasser and Feucht were looking for.

Despite spending up to a week at a time underground exploring Surtshellir, the couple always had an eye towards the heavens. Over the last ten years high-resolution cameras on Martian and lunar orbiters have spotted signs of vast underground cave systems - cave systems which were familiar to them. "It's only a short step to the Moon and Mars when you are talking about the geology of Iceland," says Feucht.

In response to these extraterrestrial cave discoveries, space agencies have begun dreaming up ingenious methods to explore and make homely these natural shelters for off-world living. What Gasser and Feucht saw in the vandalised Surtshellir cave was an opportunity to make the best of a bad situation. At the National Geographic Explorers Festival in 2016, they proposed the creation of a testing facility for the robotic explorers and habitation units required for human residence under another world. In the audience was noted American explorer Mike Dunn. Soon after hearing their talk, Dunn set up the company 4th Planet Logistics to develop and test cave technology "for eventual lunar-Mars habitation". Today Gasser and Feucht are Dunn's geological consultant and operational coordinator in Europe.

Right: **In May the US Department of Defense Subterranean Challenge competition opened, assessing new cave-exploring robots from JPL, Caltech, MIT and KAIST**

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The vision of Dunn, Gasser and Feucht is a far cry from initial interest in the subsurfaces of other worlds, inspired by lunar mining. The prophesied industry received a boost as it became clearer the Moon's more geologically active past may have done a lot of the tunnelling for them. A 2014 analysis by the Lunar Reconnaissance Orbiter camera team, led by Robert Wagner of Arizona State University, discovered 200 collapse windows into cavernous voids beneath. Soon after a Purdue team proposed these pits were our first glimpse of a vast underground network of lava tubes.

On Earth such tubes are carved out by subsurface lava flows, moving like a snake through rock. However, due to the Moon's lower gravity, the potential scale and range of these underground networks is huge. In orbit around Mars at a similar time, the Mars Reconnaissance Orbiter was finding more collapsed windows near the Red Planet's ancient volcanoes. For prospective space miners these pre-dug networks present a cost-effective route to any subsurface riches. However, for space agencies and adventurers driven by exploration rather than exploitation, the real potential is human habitation.

"On the Moon or Mars it would seem logical to use whatever existing environments are there so you don't have to expend time or money building a shelter," says Manfred von Ehrenfried, a former NASA flight controller whose latest book, *From Cave Man to Cave Martian*, was published during the earlier part of this year.

As well as time and cost savings, any pre-dug underground real estate offers protection from the constant stream of micrometeorites and high-energy particles raining down from above. In addition you can enjoy more stable temperatures, shelter from Martian dust storms and access to nutrient-rich volcanic regolith for growing food. As suspected, some of these spaces are huge. Two years ago the Japan Aerospace Exploration Agency (JAXA) discovered a 50-kilometre (31-mile) lava tube beneath the lunar surface.

Under Mars there is particular interest in caves as time capsules to reveal the planet's early formation, and whether it once hosted life – or even whether it still does. Periodic spikes in methane have been measured within the Martian atmosphere and traced underground. Some astrobiologists have suggested underground-dwelling, methane-producing microorganisms, like those found inside the Earth, as a possible source.

"There could be isolated organisms near old remnant volcanic activity. Or the next best thing is we find fossilised remains of past life," says Jekan Thanga, a space robotics expert, for whom the discovery of subsurface methane led to a focus on exploring lava tubes.

However, there are significant engineering challenges to entering the subsurface. A heavy rover driving up to the edge of an already once-collapsed ceiling raises obvious concerns, and that's before we get to a vertical descent of up to 100 metres (328 feet). Even if a rover makes it down in one piece, the cave floors are covered in rubble, posing mobility challenges. As a result, space agencies are on the lookout for new, innovative approaches. In May the latest US Department of Defense Subterranean Challenge competition opened, assessing new cave-exploring robots from NASA's Jet Propulsion Laboratory (JPL), Caltech, the Massachusetts Institute of Technology and KAIST. It followed the ESA's own open call for robots to explore the subsurface of the Moon.

One solution to pit-rim instability is to bypass the surface altogether. Dr Mark Robinson from Arizona State University has looked into aiming a lander directly into the pit. "That's the scariest of them all," says Thanga, due to the challenge of achieving the requisite entry descent and landing precision to drop into pits that are generally less than 100 metres (328 feet) wide. "But it's also probably one of the most thrilling too." Most other pit-exploration approaches fall into one of two categories: abseilers or jet-propelled gliders and hoppers.

The former has the advantage that the tethering cable can be engineered to relay power and communications to and from the surface lander. The JPL is currently pursuing this with the Axel Rover as part of its Moon Diver mission concept. However, once at the bottom, surface scramblers then risk getting stuck traversing the uneven cave floor. "They seem to always test this stuff on sand or gravely floors," says von Ehrenfried. "But in a

> "It's only a short step to the Moon and Mars when you are talking about the geology of Iceland" **Christa Feucht**

Below: Early Moon base concepts proposed using surface regolith as a shield from space radiation. Lava tubes may remove that need cave you have very little of this."

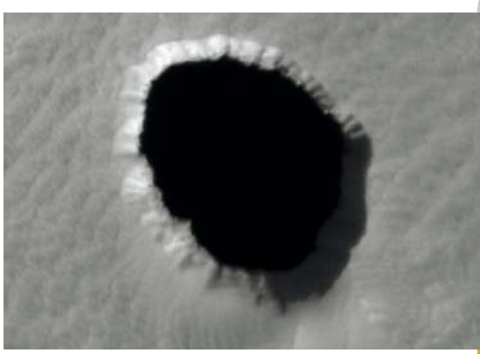
This challenge is why other robotics teams are taking to the air, or what passes for it on the Moon or Mars. This summer NASA's Mars 2020 rover was fitted with a small helicopter to explore subterranean channels. Back on Earth a project led by the Search for Extraterrestrial Intelligence (SETI) saw drones mapping Icelandic caves earlier this year with a view to future missions to the Moon.

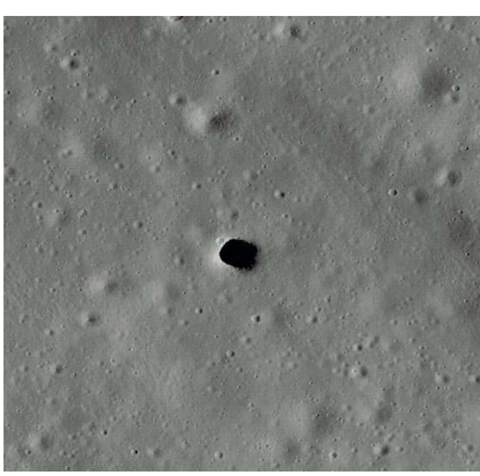
But the single flying explorer approach still carries quite a high risk. This is why microbot solutions, spreading the risk across an army of small, thruster-driven explorers, are receiving interest. The thrusters provide a soft landing, but can also power lateral exploration as the bots fan out. This ensures a greater mission range for any given amount of fuel, which is essential without solar power.

"Teams [of microbots] can also form bucket brigade teams, passing messages from one to another," says Thanga, who presented his own lunar microbot design, named the Spring Propelled Extreme Environment Robot (SPEER), at the IEEE Aerospace Conference 2019 in March.

SPEER includes a spring-powered launcher on the surface to catapult one lightweight, low-cost, spherical microbot into the pit at a time. The microbots, which would cost just $500 each to produce, have a total mass of one kilogram and include a camera and 3D laser scanners. Once on the cave floor the SPEER bots move around using thruster-powered hopping, an efficient method in low-gravity environments, especially with the addition of three-axis gyro stabilisers.

As Thanga's team build a prototype for field tests, he is realistic about the scope of any initial microbot





x2 © NASA

Alien caves

We have found evidence of subterranean environments under the surface of a number of Solar System worlds

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Earth

Earth's caves have provided a shelter for humans and our ancient ancestors for over a million years, as evidenced by fossilised remains and cave wall art. As well as lava tubes similar to those found on Mars and the Moon, Earth's atmospheric water cycles mean you also find caves within karst landscapes where water dissolves away limestone, creating a subterranean world of caverns, springs, aquifers and sinkholes.

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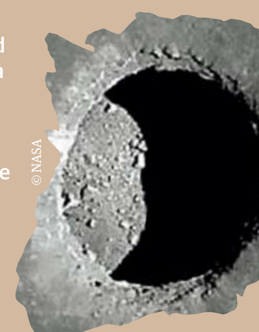
The Moon

Due to our Moon's lower gravity it was long suspected that subsurface lava flows might create extensive lava tube networks, far bigger than anything on Earth. In 2017 JAXA reported a discovery that seemed to support such a theory. It was an enormous 50-kilometre (31-mile) long, intact lava tube around the Marius Hills hole. The subsequent discovery of water ice beneath the Moon's southern pole might make exploration of the subsurface there the most realistic site for the first lunar base.



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Mars

The first evidence of Martian caves came from the three-metre-per-pixel resolution of the HiRISE camera on board the Mars Reconnaissance Orbiter, which found collapsed skylights near ancient volcanoes. Since their discovery, scientists have become interested in whether these rare windows into the Martian subsurface might settle the debate over whether life ever existed on the Red Planet, or whether it is still there. This interest increased after evidence emerged of periodic spikes in methane, which could originate underground. Some astrobiologists have suggested that microorganisms analogous to those we find on Earth could be a possible source.

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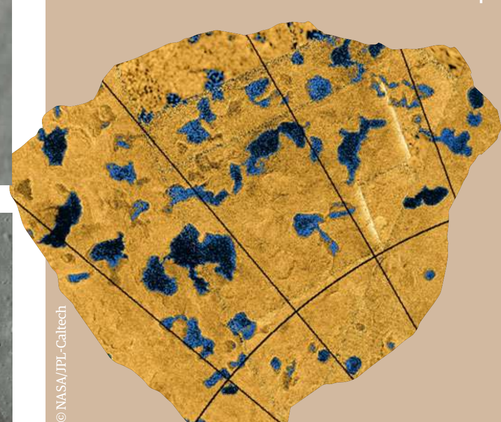

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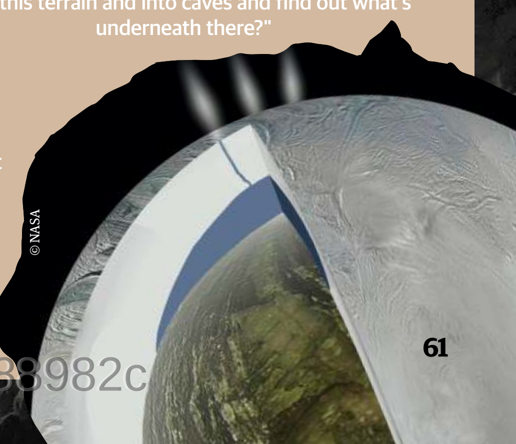
Titan

Earlier this year researchers studying rising and falling lakes on Saturn's moon Titan presented evidence that some liquid may be seeping into the rocks themselves. The result would be a karst landscape similar to those we find on Earth, with caves, springs, aquifers and sinkholes. "We've been talking about possible missions with robotic explorers that might crawl down into lava tubes and caves," said Rosaly Lopes, a planetary scientist at NASA JPL, talking to **space.com**. "Could we in the future send one of these to sort of crawl down into this terrain and into caves and find out what's underneath there?"

Enceladus

Salt-water caverns could be found beneath the surface of this small Saturnian moon. These are thought to exist between the moon's icy surface and the subsurface oceans which were discovered by Cassini. John Spencer at the Southwest Research Institute in Boulder, Colorado has suspected these caverns would be filled with water vapour at higher pressure.



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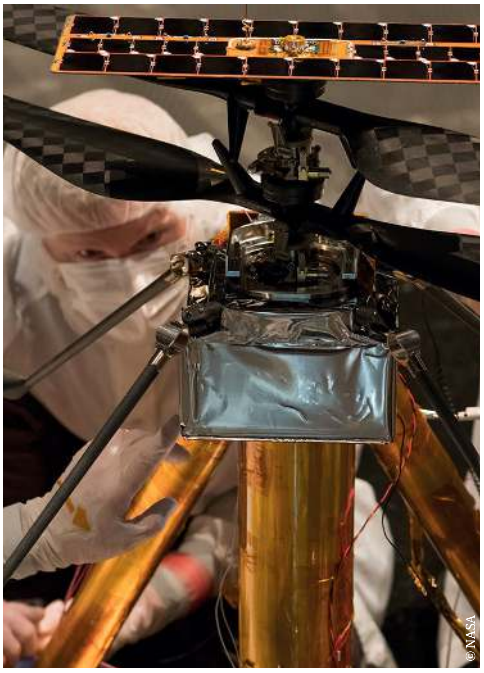

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missions, suggesting they focus on simply proving a target tube extends beyond the observable collapse pit. "As you go deeper in subsequent missions you can set up infrastructure… lines of communication, lines for power and a tunnelling system to let astronauts in and out."

It's at this point that human habitation becomes a real possibility. But before we start picking out curtains, we need to remember the three most important factors in real estate - location, location and location. And one key question in the subsurface is how deep do you go? From a radiation shielding perspective, not that far apparently.

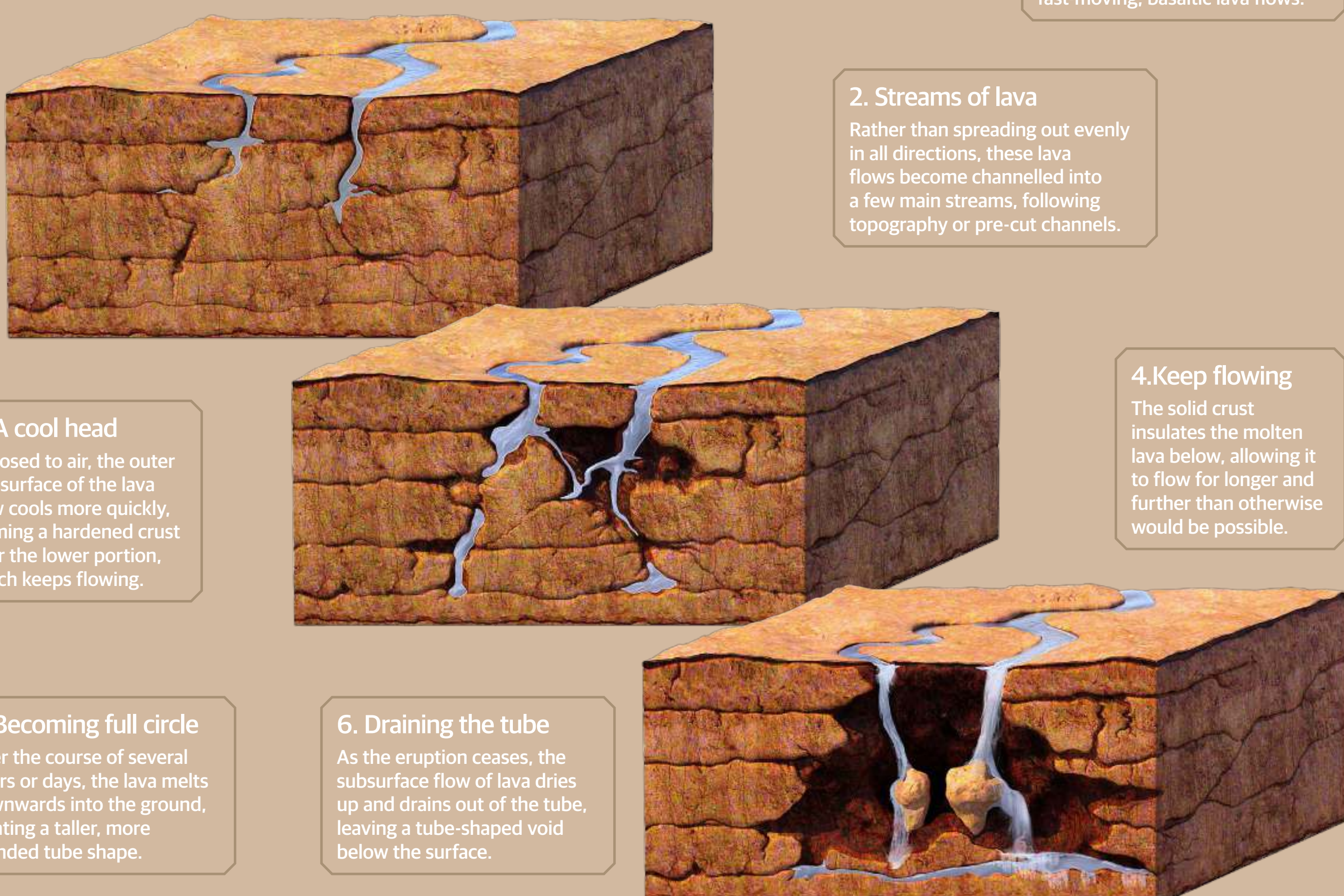
"I heard a lot of estimates, everything from a metre to two or three," says von Ehrenfried. "Some people even suggested you could get away with less than that." That doesn't mean we won't be venturing deeper for resource mining. This may also influence the choice of target cave on a planetary-wide scale. For example, the water under the Moon's south pole makes a strong case for setting up camp there. "Once you have water ice, the engineers want the water to break it up into oxygen and hydrogen, and make fuel and potable water," says von Ehrenfried.

Temperature is also a factor. It varies much less day to night the deeper you go into a cave, though this must be balanced with increasing costs of laying power and communications infrastructure. Whichever site is chosen, the next question is what structures will we, or our robotic forerunners, build? The first cave Martians will likely enjoy the latest in science and communications technology, though these will need to be specially adapted to this

> "For the people who live in caves, they perceive the cave not as scary, but as cosy. A safe place" **Martin Gasser**

Case study: how caves formed on Mars

All the evidence suggests Hawaiian-style lava tube networks are common under the Red Planet



1. Near a volcano
Lava tubes tend to form in the vicinity of shield volcanoes like those of Hawaii, which produce fast-moving, basaltic lava flows.

2. Streams of lava
Rather than spreading out evenly in all directions, these lava flows become channelled into a few main streams, following topography or pre-cut channels.

3. A cool head
Exposed to air, the outer top surface of the lava flow cools more quickly, forming a hardened crust over the lower portion, which keeps flowing.

4.Keep flowing
The solid crust insulates the molten lava below, allowing it to flow for longer and further than otherwise would be possible.

5. Becoming full circle
Over the course of several hours or days, the lava melts downwards into the ground, creating a taller, more rounded tube shape.

6. Draining the tube
As the eruption ceases, the subsurface flow of lava dries up and drains out of the tube, leaving a tube-shaped void below the surface.

© Nicholas Forder

unique underground setting.

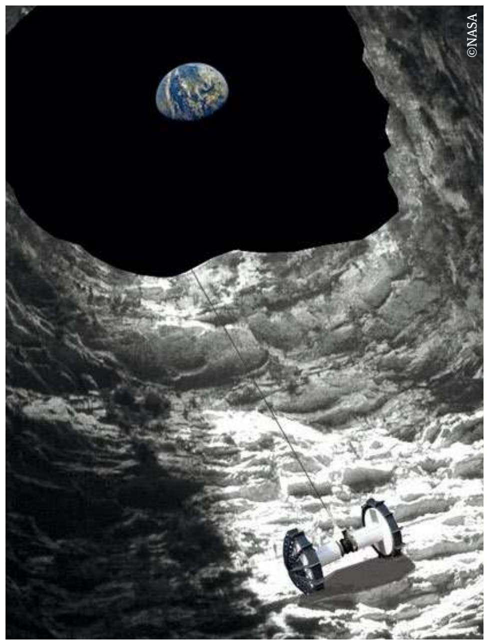
Gasser has learned from personal experience that many electromagnetic communication technologies do not work well in caves due to the magnetism of the surrounding rock. "You may need to leave a breadcrumb trail of lots of little routers," he suggests. To save on transportation some designers have taken inspiration from Bigelow Aerospace's inflatable habitation module currently being tested while attached to the International Space Station. However, such expandable material will have to be tough, warns Gasser: "There are only pointy surfaces in a cave. Any kind of habitation will have to be resistant to hard and sharp rock edges."

Though extended periods on the surface of the Moon or Mars can be harmful, Gasser can attest to the mental health struggles that come with natural light deprivation. As a result, however comfortable the home you build underground, he believes it vital to allow residents some access to the surface.

So what next? Both von Ehrenfried and Thanga believe space agency priorities for subsurface habitation seem focused on the Moon initially, particularly since the detection of polar water. Thanga, for his part, is working with planetary scientists to propose low-cost missions to get SPEER off and then under the ground. In the meantime he continues to run tests, including building mockup caves in his lab. "We're using paper mache to make the lab look like a lava tube. It's almost parallel to what the folks at Hollywood would do."

Wherever you look, momentum is building. In their roles at 4th Planet Logistics Gasser and Feucht are in talks with the ESA around rover testing to plan for future trips under the Moon, while at the start of the year a company called Astroland even began offering underground expeditions in Spain that simulate a human colony on Mars.

How realistic these tourists' experience will be to that of the first humans living under a new world is debatable. However, both ventures may in their own way change thinking around subsurface living. "For many people it's a scary thought to go into a cave and just be surrounded by rock," says Gasser. "However, for the people who live in caves, they perceive the cave not as scary, but as cosy. A safe place."



Bottom left (clockwise): This summer NASA's Mars 2020 rover was fitted with a small helicopter to explore subterranean channels

Abseiling rovers like Axel can explore caves with a tethering cable that can also relay power and communications to the surface

NASA astrobiology mission BRAILLE is using a four-wheeled NASA test rover to explore Earth's caves as practice for exploring caves on Mars and the Moon

What these caves could be used for

There are many reasons to investigate these off-world caves

Natural shelter

The subsurface network of lava tubes on Mars and the Moon can save mission time erecting shelters on the surface while also protecting astronauts from harmful radiation and micrometeorites constantly raining down.

Finding life

If life once existed on Mars, the evidence is likely to be underground. Periodic spikes in methane have been measured within the Martian atmosphere, which some astrobiologists have put forward as possible evidence of cave-dwelling, methane-producing microorganisms.

Understand the history of Mars

Current exploration of Martian geology is limited to surface layers and minor depths from rover drilling. Caves provide an opportunity to travel back millions or billions of years by reading the story preserved in lava tube walls.

Mining

Initial interest in the Moon's subsurface was in anticipation of future lunar mining. The discovery of lava tube networks might make a stronger economic case by showing a lot of excavation has already been done.

Growing food

On Earth, volcanic soils provide some of the most nutrient-rich soils available for farming. Perhaps similarly mineral-rich lunar regolith could be converted into soils to grow food that will sustain inhabitants of the first lunar bases?