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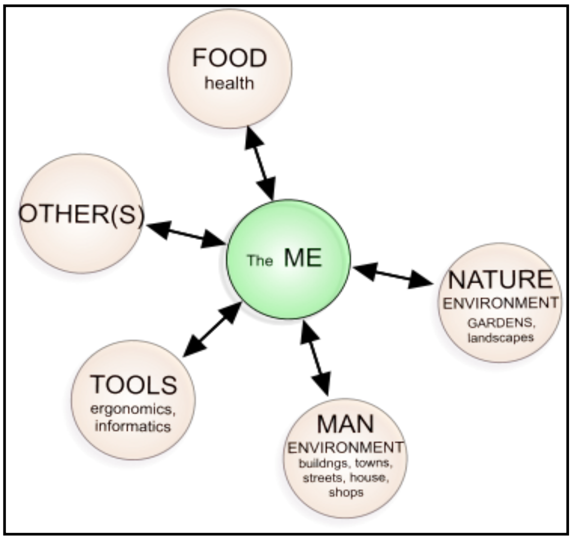

The idea that life began as clay crystals is 50 years old

In 1966, a young chemist suggested a radical new theory for how life might h

In 1966, a young chemist suggested a radical new theory for how life might have begun on Earth. Fifty years on, we ask if there was any truth in his ideas

- By Martha Henriques

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A rock is the ultimate example of inanimate, dead matter. After all, it just sits there, and only moves if it is pushed. But what if some minerals are not as stone-dead as we thought?

Chemist Graham Cairns-Smith has spent his entire scientific career pushing a simple, radical idea: life did not begin with fiddly organic molecules like DNA, but with simple crystals.

It is now 50 years since Cairns-Smith first put forward his ideas about the origin of life. Some scientists have ridiculed them; others have, cautiously or wholeheartedly, embraced them. They have never become mainstream orthodoxy, but they have never quite gone away either. Was there any truth to Cairns-Smith's daring proposal? Did life really come from crystals?

Dorothy and Graham Cairns-Smith in their home (Credit: Martha Henriques)

In June 2016 I visited Cairns-Smith and his wife Dorothy at their house on the outskirts of Glasgow, UK. Now 85, he has a rare condition related to Parkinson's disease, which has affected his mobility. However, his scientific curiosity and his sense of humour remain undimmed.

He was a dour man and he sort of muttered, 'A pity you chose science'

While he will most likely be remembered for his theories on the origin of life, his first passion was painting.

"We met when he was at Glasgow and he was doing these," says Dorothy, showing me the prolific collection lining almost every wall in the downstairs of their house. "He was going through an abstract phase."

Cairns-Smith's success as a painter eventually became too demanding. He was putting on one-man shows and getting paintings into the Royal Scottish Academy, but decided to quit and focus on science, which offered a more reliable income with which to support a family.

Cairns-Smith gave up his career in art for one in science (Credit: Martha Henriques)

"There was a man called William Crosbie, who was a very well-known Scottish painter, who was teaching him [at Glasgow]," Dorothy recalls. "He was a dour man and he sort of muttered, 'A pity you chose science'."

However, Cairns-Smith does not seem to have any regrets about his decision. Copies of his scientific books, and the sketches he drew to illustrate them, are spread across his upstairs study. They have just as much of a presence in the house as his artwork.

As a student at the University of Edinburgh in the 1950s, Cairns-Smith became fascinated by the problem of how life began.

Stanley Miller: one of the first to study life's origins (Credit: Science Photo Library)

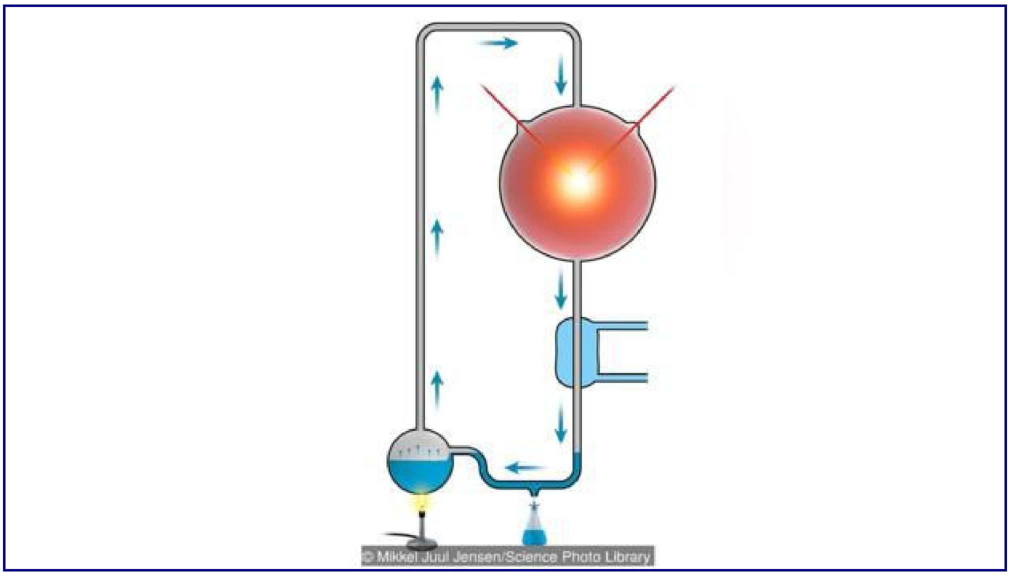
Through his studies of organic chemistry, Cairns-Smith understood that the essential molecules of life – such as DNA and proteins – could be delicate and temperamental. So how could complex molecules like these spring from the soup of simple compounds on the primordial Earth? This puzzle still occupies scientists today.

To Cairns-Smith, the experiment raised more questions than it answered

In a study published in 1953 – the same year that the structure of DNA was discovered – a biochemist called Stanley Miller sent a bolt of electricity through a mixture of gases and liquids thought to have been present on the early Earth. The spark turned these simple chemicals into some of the most basic building blocks of life: amino acids, the units that link together to make proteins.

The story hit the headlines. "Science: Semi-creation" was the headline in *Time* magazine. Miller's study became a landmark scientific paper.

But to Cairns-Smith, the experiment raised more questions than it answered.



Stanley Miller's experiment made amino acids from simple chemicals (Credit: Mikkel Juul Jensen/Science Photo Library)

Although Miller had made some of the most essential compounds of life, his experiment did not explain how they and other building blocks – such as nucleotides, which make up DNA – first came together in an ordered way, to form the complex molecules necessary for life.

His aim was to find a system much simpler than modern life

In Miller's experiment, "simpler molecules are more likely to be found and more likely to form than more complex molecules," says Cairns-Smith. "The idea you'd make a nucleotide is ridiculous. The more complicated the molecule, the less of it will form."

For Cairns-Smith, this was the real problem. He thought there had to be another stage before our elaborate system of genetic material took over.

"It was an extremely interesting experiment," says Cairns-Smith. He also describes it as "beautiful". But it did not satisfy his curiosity.

So he decided to go back to basics.

Graham Cairns-Smith (Credit: Martha Henriques)

Cairns-Smith asked himself two questions: What are the essential properties needed for a living system, and can those properties be found anywhere other than the forms of life that we know today?

If you look at clay under a microscope, you will find that it is made of tiny crystals

His aim was to find a system much simpler than modern life, but which had some of the crucial properties of a living system. He found an answer in an unlikely place: clays.

Most of us, if we think about clay at all, probably just remember how bad we were in pottery class at school. Clay, at first glance, is just a sort of damp, vaguely gritty dirt.

But Cairns-Smith knew there was more to clay than that. In an abstract way, it can be rather life-like.

A chunk of clay (Credit: Trevor Clifford Photography/Science Photo Library)

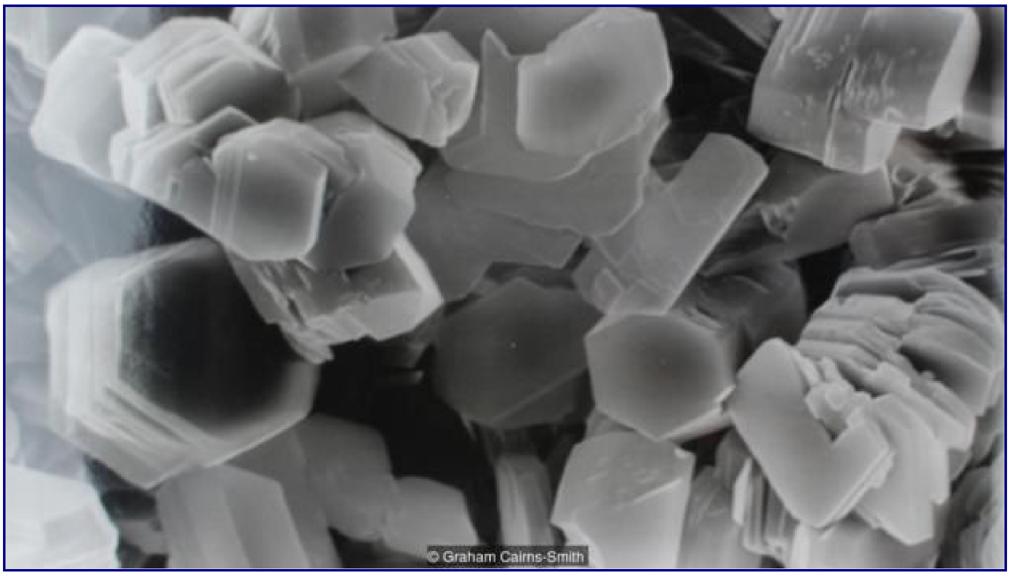
If you look at clay under a microscope, you will find that it is made of tiny crystals. Within each crystal, atoms are arranged

Crystals' essential characteristics mean they are primed to begin evolving in a structure that repeats in a tightly-packed, regular pattern.

Each crystal can grow, if it is placed in water laced with the same chemical components. Crystals can also split apart, with one "mother" crystal giving rise to "daughter" crystals.

Each crystal can even have its own peculiarities, which it can pass on to its daughter crystals – much like living things inherit traits from their parents. And sometimes, when a crystal breaks apart, new quirks can be introduced, for instance because of the stress of breaking. This is similar to the process of genetic mutation, which creates new traits in living things.

In other words, Cairns-Smith reasoned, crystals' essential characteristics mean they are primed to begin evolving.



Crystals of clay (Credit: Graham Cairns-Smith)

When a crystal passes its peculiarities onto its daughters, these unique traits could either help or hinder the new crystals.

In 50 years there have only been a handful of experiments exploring Cairns-Smith's ideas

For instance, the daughters may end up more likely to be able to split into two crystals. If the characteristics of a crystal affect its ability to split apart, then in effect that crystal has an evolutionary advantage.

In a sense, physical flaws or peculiarities in a crystal could be thought of as genetic information. As a result, Cairns-Smith thought that crystal minerals could be subject to a simple form of evolution by natural selection. This idea is now called the "crystals-as-genes hypothesis".

At a later stage, Cairns-Smith reasoned, biological molecules like DNA began to associate with the crystals. This helped the replication process. Eventually, a "genetic takeover" happened: the biological molecules developed the ability to replicate by themselves, and left the crystals behind.

Cairns-Smith set all this out in [a paper published in 1966], half a century ago.

His ideas are elegant, but there is a big problem: they have proved almost impossible to test. In 50 years there have only been a handful of experiments exploring Cairns-Smith's ideas.

Clay comes in many forms (Credit: Chassenet/BSIP/Science Photo Library)

The trouble is that there is no experimental technique for studying minerals at the tiny scales necessary to examine the processes Cairns-Smith outlined, says Dieter Braun of Ludwig Maximilian University of Munich in Germany.

Researchers would have to minutely examine nanoscale crystals, underwater, over a period of days to monitor how they behave. "That's just technologically very difficult," Braun says.

I fell in love with the book because it was so unlike a typical scientific monograph

He says we would need something analogous to genetic sequencing, the method by which researchers "read" the letters of DNA that make up the human genome. "You know, it took us 40 years to get sequencing for a molecule like DNA really working fast," says Braun.

Braun adds that geneticists had a powerful motivation to perfect DNA sequencing: it promised new medical treatments. Studying clay crystals would be equally difficult and expensive, with no practical benefit.

Even so, at least one element of Cairns-Smith's hypothesis has been put to the test.

Cairns-Smith found early success as an artist (Credit: Martha Henriques)

[Bart Kahr] is a crystallographer at New York University in the US. He first discovered Cairns-Smith's ideas when he came across one of his books in a shop in the mid-1980s.

He wanted to track how mother crystals pass on their traits to daughter crystals

"I fell in love with the book because it was so unlike a typical scientific monograph," says Kahr. "It was so impossibly rich [in] genuinely new ideas, and it was written in a kind of a literary vein, almost."

The next time Kahr saw the idea mentioned was in the mid-2000s – when it was harshly criticised.

"I was astonished that, 25 years on, people would still invoke the crystals-as-genes theory, only to knock it down by instantly saying that there's not any evidence for it whatsoever," says Kahr. "It was like a persistent straw man, that everybody felt that they had to acknowledge, but only to then pejoratively dismiss it as not ever having been tested."

Kahr decided to test it in his lab. He wanted to track how mother crystals pass on their traits to daughter crystals, to find out whether inheritance might work in clay minerals.

Crystals are never perfectly regular (Credit: AMMRF, University of Sydney/Science Photo Library)

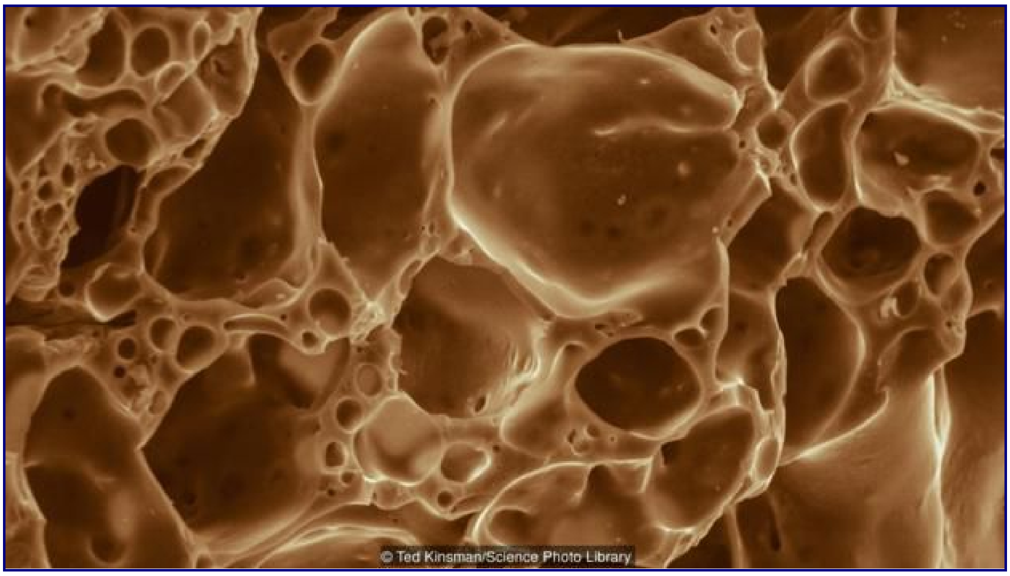
He decided to focus on a set of crystal traits called "screw dislocations". These are columns running throughout the crystal, where part of it has been nudged slightly out of alignment. Dislocations come about through the process of crystal growth, and the pattern of dislocations throughout a crystal can form a unique pattern.

Clays are just lousy crystals

Cairns-Smith had likened these irregularities to the holes in old-fashioned computer punch cards. In the same way, he supposed that these dislocations could act as a store of information.

Kahr wanted to test whether this pattern of dislocations would be inherited by the daughter crystal, and how many mutations – new dislocations – would be introduced when a daughter crystal broke off.

To avoid some of the experimental difficulties that Braun foresaw, Kahr used crystals of potassium hydrogen phthalate, which were easier to work with than clay. "Clays are just lousy crystals," he says.



Clay crystals can take many shapes (Credit: Ted Kinsman/Science Photo Library)

Kahr and his team developed a technique to map the screw dislocations of mother and daughter phthalate crystals. They found that they could see the dislocations mapping on from mother to daughter crystal quite neatly. The results were published in 2007.

Fewer mutations would have been "more like life as we know it now"

However, they were surprised by just how many additional defects appeared in the daughter crystals after they had broken off. The daughter crystals were riddled with these "mutations", and typically had at least as many new dislocations as inherited ones.

That was a problem for Cairns-Smith's ideas. If the crystals were to gradually evolve, there needed to be more inheritance than mutation, so that mothers could have a strong effect on their daughters' pattern of dislocations.

"For this to be a convincing demonstration, you can't go from a frog to a monkey in a single generation," he says. Fewer mutations would have been "more like life as we know it now".

However, Kahr is not the only one to have explored Cairns-Smith's ideas.

People have found myriad uses for clay (Credit: Ashley Cooper/Science Photo Library)

Rebecca Schulman, a bio-engineer at Johns Hopkins University in Baltimore, Maryland, was also inspired by the crystals-as-genes hypothesis.

> She had found a way to represent and copy information, in crystal form

In a series of experiments published over the last decade, she has designed a system where information is coded in a crystal structure. Rather than using naturally-occurring minerals, Schulman used crystals of nanometre-scale tiles that were made of DNA.

This DNA did not carry information in the way that it usually does in our cells. Instead, Schulman used it like Velcro to stick the tiles together in a crystal structure. It was the order of the tiles that encoded the information.

"If we could build any kind of crystal based on the very simple physical rules that we know crystals must obey, then it's possible to imagine interesting evolution processes that could emerge in relatively simple environments," she says.

Schulman found, first through computer simulation and then by experiment, that the DNA tiles could stack up in a particular pattern, effectively encoding information in a crystal structure. She had found a way to represent and copy information, in crystal form.

The early Earth was a strange place (Credit: Richard Bizley/Science Photo Library)

On a theoretical level, her findings are useful for studies of the origin of life. "Part of the goal for origin-of-life research is very broadly to ask how one can design systems in chemistry where information can be replicated," says Schulman.

> He could never get funding

However, Schulman's studies do not show that Cairns-Smith's theory is correct. For one thing, her experiments did not use clay. More broadly, just because the process works in the lab does not necessarily imply that life on Earth really began that way.

That is about it for rigorous experimental tests of the crystals-as-genes idea. Cairns-Smith himself tried for years to put his ideas to the test, but made little headway.

"He could never get funding," Dorothy says. A major stumbling block to securing research grants was that his work straddled too many different disciplines.

One of Cairns-Smith's artworks (Credit: Martha Henriques)

"One time we went to California, and Graham gave lectures to the Menlo Park Geology

Survey," says Dorothy. "They all said, well, your geology's fine but I don't think your chemistry's right. Then he gave a lecture to NASA on the chemistry side and they said, well, your chemistry's fine but I'm not sure about your biology. And then he lectured to Berkeley and they said, well, your biology's fine but I'm not sure about your geology."

> I was supremely disappointed by people who think that more complicated ideas are more likely to be true

Cairns-Smith found a more eager audience in science journalists and the popular press. Other scientists showed interest, too: the evolutionary biologist and writer Richard Dawkins discussed the crystals-as-genes hypothesis in his 1986 book *The Blind Watchmaker.*

Eventually Cairns-Smith's publisher encouraged him to write a popular science book on his ideas. Entitled *Seven Clues to the Origin of Life*, it was published in 1990. Written in the style of a murder mystery, it is about as gripping as a book on organic chemistry can get.

Cairns-Smith says he enjoyed writing for wider audiences, because putting a point simply and intuitively held a satisfaction for him. "I was supremely disappointed by people who think that more complicated ideas are more likely to be true," he says.

But despite his best efforts, his ideas did not enter the scientific mainstream.

"I'm puzzled generally speaking at why some things in science seem to catch on and others seem not to catch on," says Kahr. "There's no accounting for popular taste."

A chunk of clay (Credit: Trevor Clifford Photography/Science Photo Library)

But even if Cairns-Smith's specific ideas never pan out, there are two ways in which they continue to influence the science of the origin of life even today.

> Until now, origin of life research was really chemistry-dominated

The first is that they raise the question of what constitutes life, and offer a way in which life-like processes can arise without familiar molecules like DNA.

"It's a good idea to look around beyond what biology is really teaching us," says Braun. "Why not scope out the possibilities quite widely? I'm all in for that."

Secondly, Cairns-Smith's multidisciplinary approach – fusing biology, chemistry and geology

– was way ahead of its time.

Bacteria are some of the simplest forms of life (Credit: Christian Jegou, Publiphoto Diffusion/Science Photo Library)

"Until now, origin of life research was really chemistry-dominated," says Braun. But in the last couple of decades, it has become broader: as well as trying to make the key chemicals of life, researchers are also using genetics to work out what the earliest life was like, and using geology to figure out the conditions in which it formed.

> The specific scenario he envisaged may well be completely wrong

"I guess people will still see it as a little bit of an oddity, but he was really pointing us in the right direction," says Braun. "People now realise that life is not arising just in water in a glass flask, but in all the chemistry of the environment and from geology. That's his legacy: to say, look in more detail at rocks."

There may never be hard evidence for Cairns-Smith's ideas. "If this were to be a huge scientific enterprise, if there were huge technology behind it, there would be enough resources to really push the experiments," says Braun. "But it's really just a very small community, and this is a little bit too far out."

However, the lack of evidence will not be Cairns-Smith's real legacy. The specific scenario he envisaged may well be completely wrong. But in terms of inspiring people to look at the question of life's origin in new ways, his work has punched well above its weight.