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From Single Cells, a Vast Kingdom Arose

By CARL ZIMMER MARCH 14, 2011

Lurking in the blood of tropical snails is a single-celled creature called Capsaspora owczarzaki. This tentacled, amoebalike species is so obscure that no one even noticed it until 2002. And yet, in just a few years it has moved from anonymity to the scientific spotlight. It turns out to be one of the closest relatives to animals. As improbable as it might seem, our ancestors a billion years ago probably were a lot like Capsaspora.

The origin of animals was one of the most astonishing and important transformations in the history of life. From single-celled ancestors, they evolved into a riot of complexity and diversity. An estimated seven million species of animals live on earth today, ranging from tubeworms at the bottom of the ocean to elephants lumbering across the African savanna. Their bodies can total trillions of cells, which can develop into muscles, bones and hundreds of other kinds of tissues and cell types.

The dawn of the animal kingdom about 800 million years ago was also an ecological revolution.

Animals devoured the microbial mats that had dominated the oceans for more than two billion years and created their own habitats, like coral reefs.

The origin of animals is also one of the more mysterious episodes in the history of life. Changing from a single-celled organism to a trillion-cell collective demands a huge genetic overhaul. The intermediate species that might show how that transition took place have become extinct.

“We’re just missing the intervening steps,” said Nicole King, an evolutionary biologist at the University of California, Berkeley.

To understand how animals took on this peculiar way of life, scientists are gathering many lines of evidence. Some use rock hammers to push back the fossil record of animals by tens of millions of years. Others are finding chemical signatures of animals in ancient rocks. Still others are peering into the genomes of animals and their relatives like Capsaspora, to reconstruct the evolutionary tree of animals and their closest relatives. Surprisingly, they’ve found that a lot of the genetic equipment for building an animal was in place long before the animal kingdom even existed.

It was only in the past few years that scientists got a firm notion of what the closest relatives to animals actually are. In 2007, the National Human Genome Research Institute started an international project to compare DNA from different species and draw a family tree. The cousins of animals turn out to be a motley crew. Along with the snail-dwelling Capsaspora, our close relatives include choanoflagellates, amoebalike creatures that dwell in fresh water, where they hunt for bacteria.

Now scientists are trying to figure out how a single-celled organism like Capsaspora or choanoflagellates became a multicellular animal. Fortunately, they can get some hints from other cases in which microbes made the same transition. Plants and fungi evolved from single-celled ancestors, as well as dozens of other less familiar lineages, from brown algae seaweed to slime molds.

Primitive multicellularity may have been fairly easy to evolve. “All that has to happen is that the products of cell division stick together,” said Richard E. Michod of the University of Arizona. Once single-celled organisms shifted permanently to colonies, they could start specializing on different tasks. This division of labor made the colonies more efficient. They could grow faster than less specialized colonies.

Eventually, this division of labor could have led many cells in proto-animals to give up their ability to reproduce. Only a small group of cells still made the proteins required to produce offspring. The cells in the rest of the body could then focus on tasks like gathering food and fighting off disease.

“It’s not a hurdle,” said Bernd Schierwater of the University of Veterinary Medicine in Hanover, Germany. “It’s a very good way to be very efficient.”

Yet multicellularity also threw some new challenges at the ancestors of animals.

“When cells die in a group, they can poison each other,” said Dr. Michod. In animals, cells die in an orderly fashion, so that they release relatively few poisons. Instead, the dying cells can be recycled by their living brethren.

Another danger posed by multicellularity is the ability for a single cell to grow at the expense of others. Today that danger still looms large: cancer is the result of some cells refusing to play by the same rules as the other cells in our body.

Even simple multicellular organisms have evolved defenses to these cheaters. A group of green algae called volvox have evolved a limit to the number of times any cell can divide. “That helps reduce the potential for cells to become renegades,” said Dr. Michod.

To figure out the solutions that animals evolved, researchers are now sequencing the genomes of their single-celled relatives. They’re discovering a wealth of genes that were once thought to exist only in animals. Iñaki Ruiz-Trillo of the University of Barcelona and his colleagues searched Capsaspora’s genome for an important group of genes that encode proteins called transcription factors. Transcription factors switch other genes on and off, and some of them are vital for turning a fertilized egg into a complex animal body.

In the current issue of Molecular Biology and Evolution, Dr. Ruiz-Trillo and his colleagues report that Capsaspora shares a number of transcription factors that were once thought to be unique to animals. For example, they found a gene in Capsaspora that’s nearly identical to the animal gene brachyury. In humans and many other animal species, brachyury is essential for embryos to develop, marking a layer of cells that will become the skeleton and muscles.

Dr. Ruiz-Trillo and his colleagues have no idea what Capsaspora is doing with a brachyury gene. They’re now doing experiments to find out; in the meantime, Dr. Ruiz-Trillo speculates that single-celled relatives of animals use the brachyury gene, along with other transcription factors, to switch genes on for other tasks.

“They have to check out their environment,” said Dr. Ruiz-Trillo. “They have to mate with other organisms. They have to eat prey.”

Studies by other scientists point to the same conclusion: a lot of the genes once thought to be unique to the animal kingdom were present in the single-celled ancestors of animals. “The origin of animals depended on genes that were already in place,” Dr. King said.

In the transition to full-blown animals, Dr. King argues, these genes were co-opted for controlling a multicellular body. Old genes began to take on new functions, like producing the glue for sticking cells together and guarding against runaway cells that could become tumors.

Paleontologists have searched for decades for the fossils that chronicle this transition to the earliest animals.

Last year, Adam Maloof of Princeton and his colleagues published details of what they suggest are the oldest animal fossils yet found. The remains, found in Australia, date back 650 million years. They contain networks of pores inside of them, similar to the channels inside living sponges.

Sponges may have also left behind other ancient traces. Gordon Love of the University of California, Riverside, and his colleagues have drilled down into deposits of oil in Australia dating back at least 635 million years. In the stew of hydrocarbons they’ve brought up, they have found cholesterol-like molecules that are produced today only by one group of sponges.

The fact that sponges show up so early in the fossil record is probably no coincidence. Recent studies on animal genomes indicate that sponges are among the oldest lineages of living animals — if not the oldest. Sponges are also relatively simple compared with most other animals. They have no brains, stomachs or blood vessels.

Despite their seeming simplicity, sponges are card-carrying members of the animal kingdom. Like other animals, sponges can produce eggs and sperm, which can then produce embryos. Sponge larvae swim through the water to find their way to a good spot where they can settle down for a sedentary life and grow into adults. Their development is an exquisitely sophisticated process, with stem cells giving rise to several different cell types.

The first sponge genome was only published in August. It offered scientists an opportunity to compare the DNA of sponges to that of other animals as well as to Capsaspora and other single-celled relatives. The researchers looked at each gene in the sponge genome and tried to match it to related groups of genes in other species, known as gene families. All told, they were able to find 1,268 gene families shared by all animals — including sponges — but not by other species.

Those genes were presumably passed down to living animals from a common ancestor that lived 800 million years ago. And by surveying this catalog, scientists can infer some things about what that ancestor was like.

“It wasn’t just an amorphous blob of cells,” said Bernard M. Degnan of the University of Queensland. Instead, it was already setting aside eggs and sperm. It could produce embryos, and it could lay down complicated patterns in its body.

Animals didn’t just evolve multicellular bodies, however. They also appear to have evolved new ways of generating different kinds of bodies. Animals are more prone to mutations that shuffle sections of their proteins into new arrangements, a process called domain shuffling. “Domain shuffling seems to be a critical thing,” Dr. Degnan said.

Dr. Degnan and his colleagues have found another source of innovation in animals in a molecule called microRNA. When cells produce proteins from genes, they first make a copy of the gene in a molecule called RNA. But animal cells also make microRNAs that can attack RNA molecules and destroy them before they have a chance to make proteins. Thus they can act as another kind of switch to control gene activity.

MicroRNAs don’t seem to exist in single-celled relatives of animals. Sponges have eight microRNAs. Animals with more cell types that evolved later also evolved more microRNAs. Humans have 677, for example.

MicroRNAs and domain shuffling gave animals a powerful new source of versatility. They had the means to evolve new ways of reshaping their embryos to produce a wide range of forms — from big predators to burrowing mud-feeders.

That versatility may have allowed early animals to take advantage of changes that were unfolding all around them. About 700 million years ago, Earth emerged from the grips of a worldwide ice age. Noah Planavsky of the University of California, Riverside, and his colleagues have found evidence in rocks of that age for a sudden influx of phosphorus into the oceans at the same time. They speculate that as glaciers melted, phosphorus was washed from the exposed land into the sea.

The phosphorus may have acted as a pulse of fertilizer, stimulating algae growth. That may have been responsible for the rapid rise of oxygen in the ocean at the same time. Animals may have been prepared to use the extra oxygen to fuel large bodies and to use those bodies to devour other species.

“It was a niche to be occupied,” said Dr. Ruiz-Trillo, “and it was occupied as soon as the molecular machinery was in place.”

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