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Domesticated canaries, noticeably exhibiting carotenoid pigmentation (yellow and red) in their colorful feathers

The Puzzle of Colorful Plumage

Scientists are investigating how and why birds have developed such colorful feathers, often adorned with extravagant ornaments.

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Just like how appearance matters greatly to humans, a bird's color plays a major role in attracting a mate – a process scientists call *sexual selection*. Typically, male birds flaunt bright, eye-catching feathers, while females tend to be drab. But it's not just about color – feather shape matters, too. Some feathers evolve into elaborate ornaments, like the extravagant long tails of birds of paradise. While these flashy tails might seem like a disadvantage when it comes to escaping predators, they actually serve a purpose: impressing females. And the more impressed the females are, the better the male's chances of passing on his genes to the next generation.

The origin of coloration

Bird feathers exhibit a wide range of vibrant colors. There are two primary mechanisms governing this: structural and pigment-based coloration. *Structural* *coloration* results from the interaction of light with nano-scale structures on a feather's surface. These tiny irregularities scatter light, producing shimmering, metallic colors, like the shades of blue seen in blue tits. *Pigment-based coloration*, on the other hand, results from the presence of chemical compounds that absorb and reflect different light waves, which can be seen in a rainbow. The reflected light creates the colors we perceive. More intense colors often result from a combination of both structural and pigment-based mechanisms.

Many pigments are involved in bird coloration, including turacins (red, green, blue-green, red-violet), psittacofulvins (red, pink, orange, yellow), and pteridines (yellow, orange). However, melanins and carotenoids are the most common pigments found in birds. Melanins result in black, gray, and brown hues, while carotenoids yield yellow, red, and orange. Although over 750 types of carotenoids have been described in nature, only a small fraction are used by birds. As they are unable to synthetize such pigments on their own, birds must therefore obtain them from their diet of seeds and fruits.

Carotenoid feather coloration is widespread among birds, occurring in approximately 40% of songbird species (*Passeriformes*) as well as some (13%) non-songbird species. Plumage based on these colorful compounds has evolved independently multiple times among modern birds. The earliest known carotenoid feather pigmentation dates back 56 million years, to an ancestor of today's songbirds. In addition to coloring feathers and other tissues such as skin and fat, carotenoids are involved in several biological processes. These include antioxidation, which helps cleanse the body of harmful free radicals that can damage cells, and they are also crucial in immune responses and vitamin A production. While carotenoid pigmentation plays a role in sexual selection and may signal a bird's fitness as a mate, excessive amounts can be detrimental. Research has demonstrated the adverse effects of high carotenoid levels, such as increased stress from overproduction of free radicals in common kestrels and diminished flight efficiency in American goldfinches.

Genetic and biochemical puzzles

From a biochemical perspective, the coloration of birds can be analyzed in various ways: processing and deposition of colorful molecules in the body's tissues, pigment breakdown and regulation of pigment levels, and biochemical conversions of one type of pigment into another. Each of these biochemical processes is governed by specific molecules, whose structures are encoded by genes in the cell's DNA. Scientists are diligently working to piece these elements together into a comprehensive puzzle. So far, such work has identified a certain "genetic puzzle-piece" for each of these transformations. For example, research on canaries has identified the gene responsible for pigment deposition. This study compared white canaries, which lack this capacity, to their colorful counterparts with carotenoid pigmentation. The specific gene responsible, known as *SCARB1*, was discovered. Another gene, *BCO2*, was found to regulate the amount of carotenoids deposited in tissues by breaking them down into smaller particles. This gene encodes an enzyme that degrades beta-carotene, commonly found in carrots, and its role also relates to the sexual dichromatism observed in birds, evident in the contrasting colorations between the sexes, such as seen in the European serin.

Males of this species display lemon-yellow backs, breasts, and foreheads, while their bellies are white. Females are paler, presenting a greenish-gray hue. Not long ago, two research teams independently studied two familiar pet store species: canaries and zebra finches. They identified a gene in their DNA called *CYP2J19*, which is essential for the biochemical transformation of carotenoids that changes yellow pigments into red. However, it was later discovered that *CYP2J19* alone is insufficient for this transformation. Another missing piece in this increasingly complex puzzle was discovered through computational analyses of gene expression data from the light-sensitive elements of the retina, revealing that a gene named *BDH1L* is also responsible for the color change. This discovery demonstrated that the process is two-stage.

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A red siskin – the bird species used in creating the red canary

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Photo 1
A blue tit with visible structural feather coloration (blue color)

Photo 2
A colorful bird-of-paradise with a distinctive long tail

With the discovery of *BDH1L*'s crucial role, scientists traced the genetic source of another colorful bird variant. This time, they analyzed the orange variant of a typically red species, the red-faced parrotlet. They discovered that a mutated version of the gene (*TTC39B*) is closely linked to its orange variant. Interestingly, birds with this mutation also exhibit a deficiency in other "red" components. Their light-sensitive eye cells lack red pigments essential for seeing parts of the color spectrum. This indicates that these birds perceive the world differently from others. Additionally, it was found that this genetic element (*TTC39B*) greatly enhances the production of red ketocarotenoids in cell cultures, particularly when it can interact with two other genes – *CYP2J19* and *BDH1L*. The puzzle continues to expand, but as it grows, the emerging gaps become increasingly evident.

The red canary

Despite the fact that we still do not fully understand the molecular mechanics behind coloration, pet stores are full of vibrant birds, fish, and other creatures. Animal breeders have been able to create a stunning variety of colors, shapes, songs, and sizes through artificial selection. This doesn't require advanced knowledge of molecular biology – just a good grasp of basic genetics. By selectively breeding animals that show desirable traits, breeders can shape their offspring. For instance, noticing that bird enthusiasts wanted a red canary, breeders set about trying to create one. While wild canaries are typically a mix of gray, brown, and yellow, selective breeding has expanded their color palette to include everything from white and yellow to gray and brown. A red variety was successfully created by breeding a yellow canary with a Red Siskin, a small bird with striking red feathers. Their offspring were then bred back with yellow canaries, resulting in the vibrant red canary we see today. This process also led to the creation of mosaic canaries, which exhibit significant sexual dimorphism: the males have much more intense coloring than females, especially on their heads, wings, and tails.

As scientists continue to explore bird feather coloration, we have been discovering that it is in fact part of a much more intricate picture. We are learning that the genes behind these colors are intertwined with many other biological processes in all living things. And, as usual in science, the more we uncover, the more we realize how much we still have to learn. ■

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Further reading:

The author's doctoral thesis, *Genetic Basis of Simple and Complex Traits with Relevance to Avian Evolution*: https://www.proquest.com/openview/ea29f1d8073f123f71dba54032e0ba63/1?cbl=2026366

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