Graph theory attempts to model complex relationships through a set of nodes and another set of connecting edges. The here pictured cobweb, decorated by countless tiny droplets of dew, can be seen as a special type of graph, where the relationships between the droplets appear as strands of spider silk. However, it would not work as a genealogical tree, as there may be no cross-connections following a branching event (with the possible exception of horizontal gene transfer in simple lifeforms). On the other hand, the graph on the left, showing the termination of Lothar Colatz' recursive algorithm, would be quite suitable as a traditional genealogical tree.

A biologist's point of view

Palaeontology as a window into the past

At least since *Jean-Baptiste Lamarck* (1744-1822), it was known that organisms undergo change over the course of evolutionary time. We know from paleontology that older layers of rock contain fossilized animals of a more primeval nature, with vertebrates appearing only in later strata, following the *Cambrian explosion*. The remains of mammals and birds make their first appearances in even younger layers. The strata in the Earth's soil, which can be dated with remarkable accuracy, offer a glimpse into the distant past of our planet's history. In his ground-breaking *Philosophie Zoologique* from 1809, Lamarck was only able to show the existence of evolutionary processes – however, he was still unable to explain what caused them.

Evolution is the change of organisms in time due to selection

50 years after Lamarck's discovery, *Charles Darwin* managed to explain evolutionary changes and their causal factors:

1. *Biological evolution* means that all populations of organisms experience a change in their phenotypes over time.
2. These evolutionary changes occur exclusively in small steps, representing the difference between the parent organisms and their offspring.
3. The diversity of species stems from the branching of genealogical lines. It occurs in addition to evolutionary changes within these lines.
4. The mechanism that controls the diversification of mutations and that imprints itself on genealogical history most dramatically is *natural selection*, which Darwin described in analogy to *artificial selection* – the selective breeding of animals and plants by humans.
5. All organisms share a single common ancestor. The manifold diversity of organisms is the product of a genealogical development measuring billions of years, following the emergence of *chemical evolution*. Since this development must have started with a single species, all organisms on Earth are related.

Establishing a theory of selection

The ideas of Darwin still represent the only scientifically verifiable theory about the origin of life, and stand in stark contrast to the myriad of creation myths that are believed by different cultures throughout the world (*Genesis* being just one of many). Most of these mythologies assume a singular creation event, and a subsequent constancy of species in the biosphere.

Darwin's theory has famously sparked endless debates that still continue today – it is remarkable, however, that virtually none of these debates are based on the scientific method, including the explanations from the "intelligent design" school, which are largely pseudoscientific.

Artificial selection: waiting for specific mutations

Darwin assumed that the natural selection within populations of organisms may, on average, lead to an improvement of their biological or economical attributes. The technique of selecting and breeding animals and plants that – by pure chance – possess desirable traits was widely practiced in Darwin's day and is still being practiced today. Through continued selection over multiple breeding cycles it is possible to arrive at a breeding goal, whatever the goal may be. Breeders of ages past used to wait for so-called "hot spots" and continued to breed further offspring from such individuals. Today, we know that these "hot spots" are actually mutations – changes in hereditary information within germ cells.

Natural selection:
the difference in reproductive success of individuals

Darwin correctly recognized that selection also occurs in nature and that, in principle, it is no different from artificial selection. Natural selection is the difference in reproductive success of individuals in a population. This difference follows from varying genetic "fitness" – however, while the differences among individuals in a population are due to random mutation, the process of selection itself is not random at all, but results from the genetic constitution of each individual organism. It makes its mark on all natural populations, influencing the genetic repertoire of coming generations. Individuals more successful at reproducing – for whatever genetic reason – increase the frequency of similar genetic traits in subsequent generations.

***Survival of the fittest*: successful mutants displace the less successful ones**

Populations in nature tend to have a roughly constant size. For this reason, genetic traits that cause their hosts to be less successful at reproduction tend to disappear over time. Darwin called this the "*survival of the fittest*" – a phrase that is often misunderstood. It does not always refer to tooth-and-nail fighting, or to a naive conception of physical strength, but to a contest that is won or lost through higher or lower reproductive success. A marathon race is a good analogy. It isn't the strongest or the most violent individual that wins, but rather the one that runs fastest, by average, across of 26 miles. In evolutionary biology, this would mean that only the winner or the group of winners would be able to reproduce, and that this privilege would be upheld across many generations.

Biotic and abiotic factors of selection

Natural selection is strongly influenced by biotic and abiotic factors of the environment in which a population lives. Abiotic factors include temperature and humidity, while biotic factors comprise the myriads of interactions with other organisms – most dramatically, in the competition for natural resources.

Two-gender reproduction and meiosis

Selection is only purposeful insofar as the individuals of a population differ from each other in certain genetic traits. Among nature's earliest tricks to jumpstart selection was the emergence of sexuality with two genders, combined with a means of cell division known as meiosis. It differs from traditional cell division (mitosis) in that the chromosomes are first split in half before being recombined, leading to a unification of the parent chromosomes.

A virtually infinite number of germ cells

Mitosis, and its combination of hereditary information from two parent organisms, produces a germ cell – a so-called gamete. This has interesting consequences. Assuming roughly 1000 structural genes and two forms that a gene (allele) may take within the locus of a chromosome, there exist more than 2^{1000} possible combinations – an enormous number with more than 300 digits!

Every egg and sperm is unique

No matter how many hundreds of millions of sperm a male is able to produce during ejaculation, no pair of sperm are genetically identical. Even if all the billions of men on Earth are counted, they will never be able to produce two genetically identical pieces of sperm or spermatozoa. The same is true for the female egg. This demonstrates that recombination is a motor for practically infinite variety.

Selection may be a static process, but it is the opposite of randomness

In addition to the dazzling number of chromosomic recombinations, mutations increase the diversity of variations even further. This produces a very practical scenario for selection, as it is able to consider a virtually infinite amount of slightly varying organisms. However, selection is a static process – just as in the throwing of a dice, the singular event is of little importance, and patterns only start to emerge after many attempts. The only truly random element in the selective process is the diversity of available variations – that is to say, which structural genes are combined during meiosis, and which mutations are added into the mix. The reproductive success among these random variations is highly deterministic, and the results of this process surround us every day.

The evolution of optical sensory organs

If the possession of better optical sensory organs grants an organism a relative survival advantage, then a statistically higher number of descendants will inherit this successful attribute. If the selective pressure is very large – such as in questions of detecting a predator with speed and accuracy – then good optical sensory organs may spread relatively quickly among the population, and will also keep improving over time.

Channeling boundary conditions

The type of eyes that evolve depends on many preconditions, such as the environment in which the population lives. The physical attributes of the environment constantly enforce

channeling boundary conditions – for instance, the production of a sharp image on a retina is dependent on the optical laws of refraction. For such reasons, eyes that are predominantly used at night are constructed differently from those that are usually applied during the day.

The successive evolution of different types of eyes

Our distant ancestors had to evolve successive techniques and constructions for the purpose of light perception, and for the subsequent signal processing through the nervous system. In fact, through the study of contemporary animals, it is possible to arrange an order in which our eyes must have evolved – from the humblest of beginnings to the most sophisticated lens eyes.

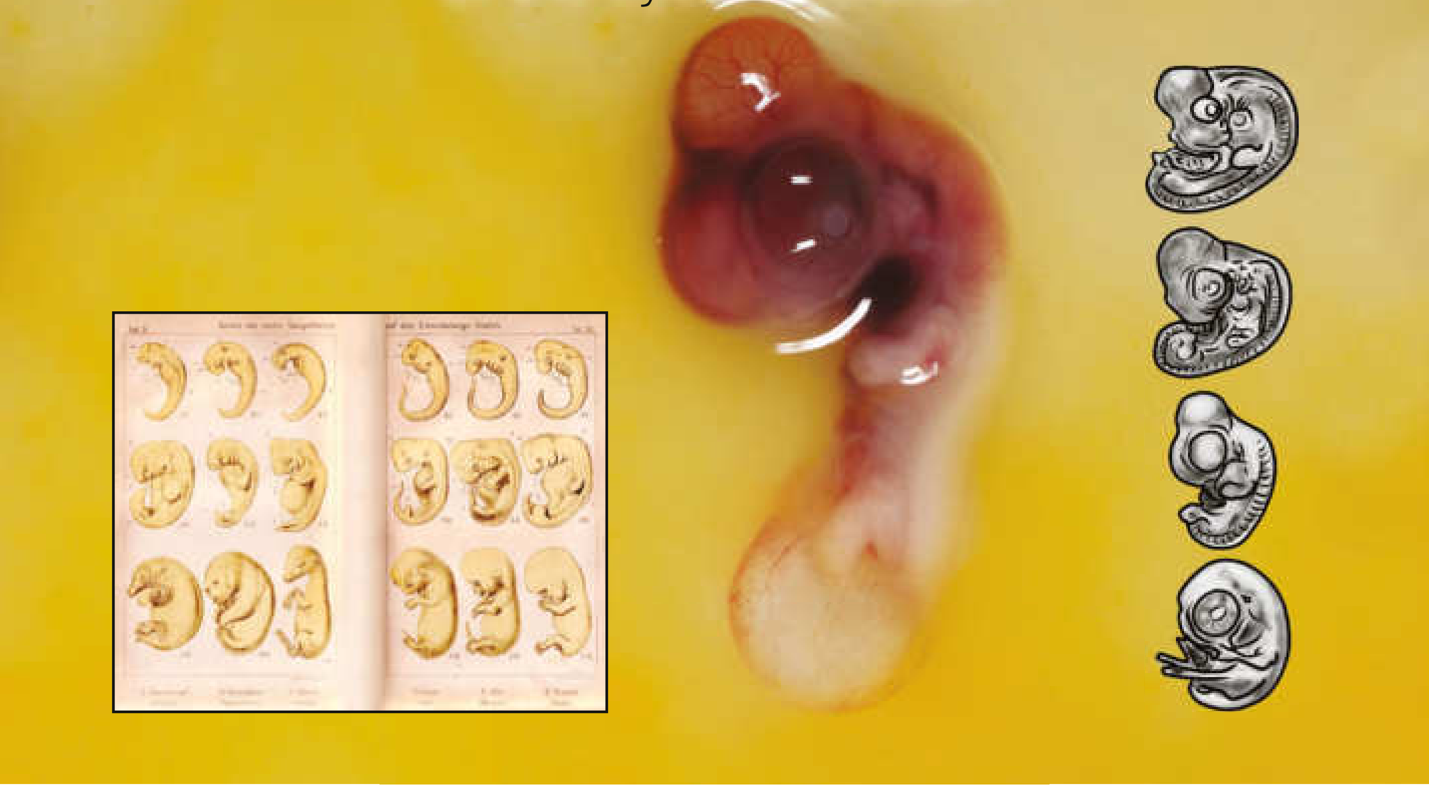
Detecting light and darkness

The earliest form of the eye represents no more than a single cell with a photo-sensitive protein pigment. Photo receptors absorb the energy of the incoming photons with a receptor protein, which changes the conformation of carbon atoms – the spatial arrangement of the rotating attachments. A form of signal processing thus emerges, wherein ion channels within the membranes are opened and closed, leading to a change of the membranic potential within the protoreceptor cell. Single cells of this type are initially only able to discern light from darkness, or very simple shadow phenomena.

A combination of modules

The detection of directional light is accomplished by adding another cell with a light-absorbing pigment. This very basic equipment – the precursor to all later types of eyes – appears to have evolved very early in the history of life on Earth. From this basic module, different types of eyes have subsequently evolved, and often completely independently of each other.

The embryo and all stages of the eye's evolution



The zoologist *Ernst Haeckel* (1843-1919) was among the earliest and most passionate advocates for the theory of evolution in the German-speaking world – in fact, he extended Darwin's idea to form a special hereditary theory of animals. As a comparative anatomist, he was inspired by the observations of the Estonian naturalist, anthropologist, and embryologist *Karl Ernst von Baer*, who by that time had already noticed that the embryos of mammals are remarkably similar to each other. By extrapolating Baer's discovery, *Haeckel* formulated his "biogenetic law" that is cited to this day, stating that a recapitulation of phylogeny occurs during ontogenesis. He postulated an evolutionary causal relationship between embryological development and the phylogeny of a species, and visualized this relationship through a sketch that is still famous today, showing the embryonic stages of eight different vertebrates – including fish, amphibians, reptiles, birds, and humans. *Haeckel* stated that these embryos share a strong resemblance during early developmental stages, with the most dramatic differences occurring only later. From this observation, he concluded that the embryos of the first vertebrates must have looked like the contemporary common form at the start of embryonic development. While this statement later turned out to be too simplified, the basic assumption is correct: the early traits of embryos are also subject to selection. Today, these ideas have produced their own branch of biological science – developmental evolutionary biology, often abbreviated as "EvoDevo".

Today's understanding of biogenetic law builds upon the observation that an organism is a system that is subject to perpetual change and reconstruction.

E. Haeckel **Generelle Morphologie der Organismen** 1866

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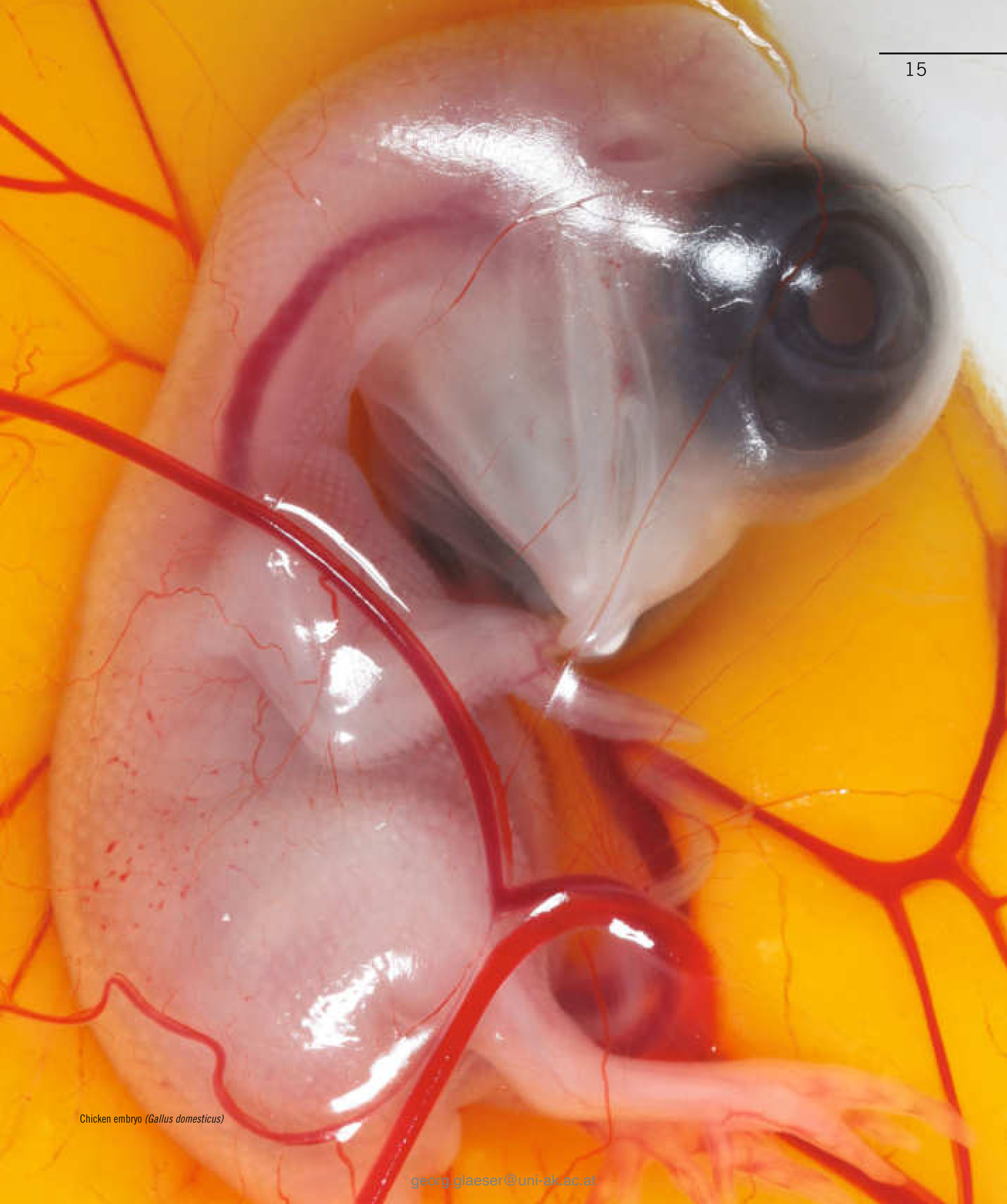

Chicken embryo *(Gallus domesticus)*