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Tracking evolution

Instructions for the board game

Goal

The aim of the game is to evolve into a modern organism, starting from the *Last Universal Common Ancestor* (LUCA). If you want to win, you will need to evolve faster than the other players. It is not important whether you finish as a kangaroo, a juniper bush or a spider — what matters is finishing before the others in this 'struggle for existence'.

Requirements

Up to six people can play the game at the same time. The minimum number of players is two. Every player should have unique counter or token to indicate their position on the board. At least one six-sided die is required, but the game will be easier to play with three of them. Sometimes it is helpful to mark a position on the board. For this you can use an extra token, a pencil or anything else of a similar size.

The 'game master'

We suggest that you should choose someone to be the 'game master'. This is not obligatory, but it makes the game easier to play. The game master can be a player as well, but he or she will have some extra duties. The game master will be responsible for ensuring that the rules are followed and will read aloud the descriptions and rules.

If you decide to play without a game master, all players will need to read the descriptions on the following pages and we recommend that this is done aloud, so that everyone knows what decisions have to be made and their evolutionary consequences.

Playing the game

To start, all players must place their counters/tokens on the area of the board described as LUCA. Players then take it in turns to roll the die and move forward as follows:

To move his or her counter each player must roll one die. The number of spots on the die indicates how many positions they should move forward on the board.

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If a player encounters a numbered black circle on the board, this indicates a *special evolutionary event*. Descriptions of the events are given on the following pages. The outcome of the events determine the direction of the next move; this is chosen by a second throw of one or more dice. The die symbols (★) indicate how many dice should be thrown at each numbered position; the arrows (△, ▷ or ◁) show the direction of the next move.

When a player encounters a numbered black circle, the game master should state how many dice must be thrown. According to the score obtained when the dice have been thrown, the game master should then state whether the player should turn left or right and read aloud the appropriate description of the special evolutionary event.

A player must repeat the procedure described in 2 (above) every time he or she encounters a numbered black circle, *even within the same turn*.

Special evolutionary events

You start the game as a *Last Universal Common Ancestor* of all contemporary organisms — a simple (chemo) autotrophic cell, which obtains energy by oxidising inorganic compounds. On your route to modern times, you experience several *Special evolutionary events*.

1 Archaea or bacteria? ★

If you score four or more

- ▷ Accumulation of minor changes in rRNA and some enzymes sets you on the evolutionary path leading to Archaea.

If you score less than four

- ◁ You remain in the classic lineage of bacteria.

2 Photosynthesis ★

If you score six

- ▷ You acquire the ability to synthesize chlorophyll and hence to convert light energy from the sun into chemical energy by photosynthesis [Cyanobacteria].

If you score less than six

- ◁ You remain in the classic lineage of bacteria.

3 Mitochondria ★ ★

If you score three or more

- ▷ You are devoured by a single-celled organism, but you are lucky and avoid digestion. You enter into co-operation with your new host and, as an endosymbiont

(a mitochondrion), you help it to utilise energy. From this day forward, your fates are bound and you evolve with Eukaryota.

If you score two

△ You remain in the classic lineage of bacteria.

4 Chloroplasts *

If you score two or more

▷ You are devoured by a single-celled eukaryotic organism, but you are lucky and avoid digestion. You enter into co-operation with your new host, and are able to utilise energy from sunlight (as a chloroplast). From now on, you evolve with eukaryotic plants.

If you score one

△ You remain within the classic lineage of cyanobacteria.

5 Nucleus and tubulin * *

If you score three or more

▷ You organise your genetic material in chromosomes in a brand new way: within a membrane-bound cell nucleus. Development of tubulin enables you to form spindle apparatus and use it for mitotic fission (mitosis). You also acquire the ability of amoeboid movement and phagocytosis [Eukaryota].

If you score two

◁ You remain in the classic lineage of archaea.

6 Ciliates * *

If you score three or more

▷ You remain in the classic lineage of eukaryota.

If you score two

◁ You organise your genetic material in a new way by splitting it into two parts, one of which is used only during reproduction (micronucleus), while the other serves for everyday protein production (macronucleus). In the course of time, you form short, synchronously working flagella (cilia) on the whole surface of the cell [Ciliates].

7 Flagella * *

If you score three or more

▷ You remain in the classic lineage of eukaryota.

If you score two

◁ You lose the ability to absorb materials by phagocytosis. You generate two propulsive flagella at the front of the cell [Flagellates].

8 Cell wall and flagellum * *

If you score ten or more

- ▷ You form a cell wall from fibrils of cellulose [Algae/Plants].

If you score less than ten

- ◁ You form a single propulsive flagellum [Fungi/Animals].

9 Animals and fungi * * *

If you score seven or more

- ▷ You gain the capacity to produce collagen, which creates complex protein webs that stiffen the cell membrane. In the course of time, with others like yourself, you form clusters of cells that start to specialise [Animals].

If you score less than seven

- ◁ You begin to form a chitinous cell wall and filiform, multicellular structures. In the course of time, you acquire the capacity to live in a terrestrial environment [Fungi].

10 Spore generation *

If you score four or more

- ▷ You begin to generate complex structures from compact hyphae to support basidia that bear external spores for sexual reproduction [Basidiomycota].

If you score less than four

- ◁ You gain the capacity to produce highly-resilient 'resting' spores [Zygomycota].

11 Two cell layers and sponges * * *

If you score six or more

- ▷ Basement membrane formation enables your cells to organise in two layers of tissues [Eumetazoa].

If you score less than six

- ◁ Your lifestyle becomes sedentary; you generate an internal skeleton of stiffened rods made of calcium carbonate or silica (spicules). This is used both for structure and protection [Sponges].

12 Three cell layers and Cnidaria * * *

If you score six or more

- ▷ You gain bilateral symmetry and your cells also form three layers [Bilateria].

If you score less than six

- ◁ Some of your cells (cnidocytes or nematocysts) become venomous and are used for hunting and defence. Your life cycle becomes more complex: due to alternation of generations it changes repeatedly from sedentary to motile [Cnidaria].

13 A protective epidermis? * * *

If you score ten or more

- ▷ You lose the capability to synthesize chitin [Flatworms/Deuterostomes].

If you score less than ten

- ◁ Your epidermis starts production of an amorphous protective cuticle. [Aschelminthes/Arthropods/Annelids/Molluscs].

14 Moulting *

If you score five or more

- ▷ You remain in the classic lineage of invertebrates, crawling over the seabed [Annelids/Molluscs].

If you score less than five

- ◁ As your cuticle gets tougher, you need to moult in order to grow [Arthropods/Aschelminthes].

15 Arthropods *

If you score two or more

- ▷ You form a hard exoskeleton made of chitin and numerous appendages consisting of a series of segments [Arthropods].

If you score one

- ◁ You remain within the classic lineage of moulting invertebrates [Aschelminthes].

16 Annelids and molluscs *

If you score three or more

- ▷ You gain a mantle, which protects your internal organs and produces a shell. You also form a toothed chitinous ribbon for cutting and chewing food (a radula) [Molluscs].

If you score one or two

- ◁ Your body becomes segmented (metameric). In the course of time, your individual segments perform specialised functions [Annelids].

17 Flatworms * *

If you score four or more

- ▷ You form a brand new mouth while the old mouth (blastopore) becomes an anus [Deuterostomes].

If you score less than four

- ◁ You stay with in the classic lineage of invertebrates that are unable to synthesize chitin [Flatworms].

18 Crustaceans and arachnids * *

If you score six or more

- ▷ [Crustaceans/Uniramia].

If you score less than six

- ◁ You colonise a terrestrial habitat and reduce the number of legs to four pairs. Your head and body segments merge to form a cephalothorax, and you gain spinnerets (silk glands) [Arachnids].

19 Insects and crustaceans *

If you score three or more

- ▷ You colonise a terrestrial habitat and reduce the number of legs to three pairs. You start breathing with tracheae, and form two pairs of exoskeleton outgrowths that enable flying (wings) [Insects].

If you score less than three

- ◁ You remain in an aquatic habitat and your head and body segments merge to form a cephalothorax. Gradually, you gain the ability to live on land, but you never stray far from water [Crustaceans].

20 Beetles, bees and ants *

If you score four or more

- ▷ From your first pair of wings, you form hardened shield-like forewings [Beetles].

If you score less than four

- ◁ You start to live in a communities [Hymenoptera: sawflies, wasps, bees and ants].

21 Bivalves and snails *

If you score four or more

- ▷ Gradually you stop using your radula to obtain food and become a filter feeder. In addition, you generate a two-piece, hinged shell [Bivalves].

If you score less than four

- ◁ Gradually, your shell gets twisted asymmetrically and you slowly start to conquer the terrestrial habitat [Snails].

22 Vertebrates and echinoderms * * *

If you score six or more

- ▷ You gain seven gill openings and a flexible rod (the notochord) to which your laterally-placed muscles can attach. You develop a complex internal skeleton, which stiffens your body and makes the development of fins, jaws and scales possible [Vertebrates].

If you score less than six

- ◁ Your body develops five-fold radial symmetry [Echinoderms].

23 Bony or cartilaginous fish * * *

If you score six or more

- ▷ You form a bony skeleton [Osteichthyes or bony fishes].

If you score less than six

- ◁ You remain within the classic lineage of fishes [Chondrichthyes or cartilaginous fishes].

24 Amphibians and bony fishes * * *

If you score six or more

- ▷ You start to creep on land; you form lungs and transform fins into walking limbs [Amphibians].

If you score less than six

- ◁ You gain a swim bladder, allowing you to regulate the depth to which you dive and an operculum — a hard bony flap covering and protecting the gills [Bony fishes].

25 Reptiles and amphibians * * *

If you score six or more

- ▷ You develop a watertight skin covered with scales. You are on your way to developing a four-chambered heart. You become independent of the aquatic habitat by producing eggs covered with leathery or calcareous shells that reduce water loss [Reptiles].

If you score less than six

- ◁ You remain in the classic lineage of amphibians [Amphibians].

26 Mammals *

If you score three or more

▷ You remain in the classic lineage of reptiles.

If you score less than three

◁ Your limbs become parasagittal (that is, placed on either side of your body). Your teeth start to differentiate depending on their function and you develop fur which enables you to maintain a stable body temperature. You start feeding your offspring with milk from mammary glands [Mammals].

27 Placental mammal or marsupial? ★

If you score three or more

▷ You lengthen your pregnancy and to improve your foetus's development; you form a special organ for the delivery of nutrients and exchange of gases between mother and child (placenta) [Eutheria].

If you score less than three

◁ You develop a pouch to rear your offspring through early infancy [Marsupials].

28 Primates and bats ★

If you score four or more

▷ You develop an opposable thumb, which makes it easier for you to grip branches. Your eyes shift to the front of your head, so you gain stereoscopic vision. Gradually your brain develops. In addition, you develop bipedal locomotion, leaving your arms available for manipulating objects with your hands. Development of the larynx results in complex vocalisation and, ultimately, speech. In the course of time, you begin to create tools and start using abstract ideas [Primates].

If you score less than four

◁ You develop a membrane between your limbs which makes limited gliding possible, which in turn makes it easier to chase insects. In the course of time you gain the ability to fly, and develop excellent hearing which you use for precise orientation in space (echolocation) [Bats].

29 Turtles ★

If you score two or more

▷ You remain within the classic lineage of reptiles.

If you score one

◁ You form an bony or cartilaginous shell from ribs, backbone and clavicles [Turtles].

30 Crocodiles, lizards and snakes ★

If you score three or more

- ▷ You develop a four-chambered heart [Crocodiles].

If you score one or two

- ◁ You develop a new way of moving: lateral undulation, which improves your speed and agility [Squamata: Lizards and snakes].

31 Snakes ★

If you score four or more

- ▷ Your body elongates remarkably. You renounce your limbs in favour of efficient crawling. Your jaws evolve so that you are able to swallow even very large prey with ease [Snakes].

If you score less than four

- ◁ You remain within the classic lineage of lizards.

32 Crocodiles and birds ★

If you score five or more

- ▷ You return to an amphibian lifestyle as you gain a massive tail that provides propulsion through the water [Crocodiles].

If you score less than five

- ◁ Your forelimbs transform into wings and your scales develop into feathers; your pubic bones are directed backwards which makes your pelvis open and enables you to lay big eggs [Birds].

33 Owls and penguins ★

If you score four or more

- ▷ You improve your flying abilities. In addition, your eyes are shifted to the front of your head, which allows for stereo vision and greatly improved hearing [Owls].

If you score less than four

- ◁ You renounce flying and develop the ability to swim and dive. Your adapted wings provide excellent 'oars' under water [Penguins].

34 Algae and plants ★

If you score six

- ▷ You remain in the classic lineage of green algae.

If you score less than six

- ◁ In the course of time, you develop multicellular forms. Your haploid phase becomes a flat ground-hugging layer (thallus) with root-like structures (rhizoids) on its

underside and multicellular reproductive organs on the top, from which your diploid phase originates [Plants].

35 Vascular plants and bryophytes ★

If you score two or more

- ▷ In your life cycle the diploid spore-producing (sporophyte) form becomes the main generation phase. The development of lignin allows the stiffening of long pipes, building vascular tissue, which in turn enables you to reach greater size. Gradually, you generate roots and shoots [Vascular plants].

If you score one

- ◁ In your life cycle, the haploid gamete-producing (gametophyte) form becomes the main generation phase. You make an attempt to conquer the terrestrial habitat, generating stem, leaves and root-like anchoring structures (rhizoids) [Bryophytes].

36 Ferns and horsetails ★

If you score two or more

- ▷ By merging shoots you form leaves, on which spore-producing organs (sporangia) develop. In the course of time, you develop a complex reproductive system consisting of micro- and megasporangia [Ferns].

If you score one

- ◁ Your spore-producing organs (sporangia) group to form cone-like structures, and your small leaves grow in whorls on hollow and jointed stems [Horsetails].

37 Seed-producing plants ★

If you score two or more

- ▷ You shrink the male gametophyte dramatically — its reduction in mass, together with the generation of air sacs, enables it to be carried by wind (pollen). This makes fertilization independent of water. You form a seed coat, under which the haploid tissue of the female gametophyte (ovule) transforms into a supply of nutrients for the developing embryo [Spermatophytes: Seed-producing plants].

If you score one

- ◁ You remain within the classic lineage of ferns.

38 Ginkgoes ★ ★

If you score six or more

- ▷ You remain within the classic lineage of spermatophytes.

If you score less than six

- ◁ You generate leaves that are fan-shaped and two-lobed [Ginkgoaceae].

39 Flowering plants *

If you score three or more

- ▷ You generate bisexual flowers and start using insects as pollinators; you also form fruits, which facilitate long-distance seed dispersal *via* animals [Flowering plants].

If you score one or two

- ◁ You remain within the classic lineage of seed-producing plants [Spermatophytes].

40 Monocotyledons *

If you score four or more

- ▷ You reduce the number of seed leaves in the ovule to one [Monocots].

If you score less than four

- ◁ You remain within the classic lineage of flowering plants.

41 Green and brown algae **

If you score eleven or twelve

- ▷ You begin to use chlorophyll B in addition to chlorophyll A, and starch becomes your main storage compound [Green algae].

If you score ten or less

- ◁ You begin to use chlorophyll C in addition to chlorophyll A, and it is laminarin that becomes your storage polysaccharide [Brown algae].

42 Chloroplasts **

If you score three or more

- △ You remain in the classic lineage of green algae.

If you score two

- ◁ You are devoured by a single-celled eukaryotic organism with flagella, but you are lucky to avoid digestion. You start to cooperate with your new host and enable it to harness energy from sunlight by photosynthesis.

43 Spirogyra *

If you score four or more

- ▷ You remain in the classic lineage of green algae.

If you score less than four

- ◁ You join others like you and form threadlike colonies [Spirogyrae].

Author's note

When I was preparing this game, I hoped to enlighten students (and maybe not only students) about a few important aspects of evolution, which are omitted or insufficiently emphasised in schools — at least in Poland. A board game has several limitations, however. Some of these may lead to misunderstandings, which I would like to discuss here.

Firstly, the evolutionary tree presented in the game is not the only valid one that could be produced. Despite advanced molecular techniques and a large (but still insufficient) amount of fossil evidence, opinions about evolutionary trees, especially their lower branches, are still under discussion and undergo constant revision. Consequently there may be differences between information presented in the game and that which may be found elsewhere. This does not mean that one of the sources is wrong. Rather, we should assume that we are approaching the boundaries of the unknown.

Despite compelling recent evidence from molecular phylogenetics, in constructing the game, I have used a fossil-based tree as the standard. One of the most important reasons for this is that such trees are inseparably related to the history of Earth and may be easily divided into periods, such as geological eras.

The game does not include all groups of living organisms. I have focused on the taxa that are discussed in Polish schools and I have omitted a wide range of other groups, which are quite often very important and interesting from evolutionary point of view. The full representation of our knowledge about the evolution of life on Earth would not be possible in a board game.

The relative abundance of particular taxonomic groups is not represented in any way. Such representation would cause of certain groups to dominate (like the arthropoda or, among vertebrates, the fishes) and push aside less numerous taxa, which are important to demonstrate the diversity of life. Moreover it would affect the playability of the game — 90% of players would finish as beetles!

The game presents features of living beings that have led to new branches of the evolutionary tree. These have been greatly simplified. Not all of the features of a particular species or taxon are given in the descriptions — only the more important ones. Some of the features developed gradually; sometimes this happened over many millions of years.

The species is difficult to define and even among modern organisms it is impossible to make a strict

distinction between two species. The mechanism presented in the game is again a simplification, forced by the nature of the board game. In particular, speciation is not the result of modification of a single organism, but it arises instead from the evolution of the whole population of a species. Therefore the comments in the instructions, although directed to a player as an individual, should be considered as information about a group of organisms.

I hope that despite these inaccuracies the game will prove not only an interesting source of knowledge but that it will also give students much enjoyment.

Further information

Books

Tudge, C. (2002) *The variety of life: A survey and a celebration of all the creatures that have ever lived*. Oxford University Press, Oxford.
ISBN: 0 198 60426 2.

Dawkins, R. (2004) *The ancestor's tale. A pilgrimage to the dawn of life*. Weidenfeld and Nicolson, London. ISBN: 0 297 82503 8.

Prothero, D. (2007) *Evolution: What the fossils say and why it matters*. Columbia University Press, New York. ISBN: 0 231 13962 4.

Web sites

The Tree of Life web project

<http://tolweb.org/tree>

Interactive Tree of Life

<http://itol.embl.de>

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