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Early evolution of evolutionary thinking: teaching biological evolution in elementary schools

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Abstract

Background: Evolution is considered the unifying concept in biology and is also a key theory underlying many areas of human knowledge. Teaching evolution from as early as kindergarten allows children to better understand concepts related with the biological world and prevents the development of negative feelings and misconceptions about the theory of evolution. However, evolution is absent from most of the educational curricula in the early school grades, even though some of its central concepts are common contents in the curricula of these initial years.

Methods: In the present paper we present a set of activities that can be performed with elementary school students to explore and understand evolution and its impact on biological diversity, while promoting critical thinking and scientific literacy. These activities explore concepts of intra-specific diversity, genealogy and inheritance, natural selection, genetic drift, and systematics, using contexts that are familiar to students, and were articulated with the Portuguese official curriculum. Similar contents are present in elementary school curricula of other countries, namely Brazil, United Kingdom, France, United States of America, Canada, or Mozambique, and therefore the same activities can potentially be used in many different countries.

Results and conclusions: Regardless of the complexity of the theory behind these concepts, our experience revealed that using these activities children were able to understand basic evolutionary mechanisms and to apply this knowledge in real case scenarios.

Keywords: Evolution; Intra-specific diversity; Natural selection; Genetic drift; Genealogical and evolutionary trees; Active learning

Background

The characteristics of all living beings as well as their ecological interactions are the result of a long evolutionary history. As such, evolution is a major unifying concept that links all the sub-disciplines of biology (National Academy of Sciences (NAS) 1998; National Science Teachers Association (NSTA) 2003; National Research Council (NRC) 2011). Knowledge on evolution is essential for students to integrate concepts in a wider framework and to achieve a clear understanding of the topics in biology curricula and of biological systems in general (Jenkins 2009). But evolution is not an exclusive property of the natural world and knowledge on evolutionary mechanisms also deeply impacted research areas as distinct as medicine, psychology, engineering, economics, informatics, and linguistics (Bull and Wichman 2001).

Despite its fundamental importance in biology and many other research fields, studies have shown that biological evolution is not yet accepted as a valid scientific theory by an important fraction of citizens from different nations (Miller et al. 2006), and that misconceptions about evolution are frequent and shared by the general public, students, and teachers from several countries (Rutledge and Warden 2000; Nehm and Reilly 2007; Prinou et al. 2011; Spiegel et al. 2012). Furthermore, these misconceptions revealed to be persistent and difficult to overcome, even when applying learning programs specifically designed to promote such conceptual changes (Bishop and Anderson 1986; Nehm and Reilly 2007). These observations led several researchers to propose an early exploration of evolutionary biology at elementary school or even kindergarten (Nadelson et al. 2009; Hermann 2011; Wagler 2010, 2012 and references therein). In agreement with this

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view, several countries explicitly include, or intend to include, evolution in their official curricula for elementary schools (see as examples the Canadian curriculum or the United Kingdom draft curriculum in Additional file 1; Berti et al., 2010 and Prinou et al. 2011 for Italian and Greek curricula, respectively). However, in some of these cases evolutionary mechanisms are not explored and evolution is only mentioned in the context of adaptation, preventing students to understand the real impact of evolution in biological diversity (Prinou et al. 2011; Wagler 2012). In other countries, including Portugal, evolution or adaptation are absent from the official programs of elementary school. But at kindergarten or elementary school age, children are already able to think critically and abstractly, to engage in scientific enquiry and, when taught about evolution, to incorporate and apply this knowledge in future responses (see Berti et al., 2010 and reviews in NRC 2007; Nadelson et al. 2009; Wagler 2012). Also, the key concepts that are required to understand biological evolution are simple, and students need only to recognize: (1) the existence of intra-specific variability; (2) that part of this variability can be transmitted over generations; (3) that the frequency of variable traits may change over generations; and (4) that these changes may cause the emergence of distinct species over time. These contents are common to official elementary school programs worldwide and can be easily explored using examples, facts, and problems that are part of students' daily life (Additional file 1; Prinou et al. 2011).

Here we present five activities developed to explore evolution in Portuguese elementary schools under contents that are present in the official curricula (Additional file 1). In order to allow using the activities in other countries, we also contextualize them in elementary school curricula from several European, American, and African countries. This set of activities was successfully used in two Portuguese elementary schools, in seven classes representing the four years of elementary education (with children aged from 5 to 10 years old). Since identical contents are present in the official curricula of other countries (see the examples in Additional file 1; Brasil. Secretaria de Educação Fundamental 1997; Espírito Santo. Secretaria de Estado de Educação 1997; Ministère de l'Éducation 2009; Ministère de Éducation Nationale 2012; INDE/MINED 2003; Ministério da Educação 2001, 2004; Department of Education 2012; NRC 1996) we anticipate that these activities can easily be implemented in many different countries using similar strategies.

Methods and Results

The activities were designed to engage students, fostering their curiosity, interest, and knowledge on evolution and were developed as structured inquiry-based lessons (NSTA 2004; NRC 2007; Banchi and Bell 2008). For that purpose, each activity starts with a class discussion about the major concepts being addressed. This allows an efficient evaluation of previous knowledge and misconceptions about the nature of science, the characteristics of organisms, heredity, species-environment interactions, the biological system of classification, and how humans impact the natural world. Students should be encouraged to discuss observations, to elaborate and discuss hypotheses and adequate testing designs, and to interpret, discuss and communicate results, in order to develop the skills required for them to achieve scientific proficiency (NRC 2007, 2012). To be more effective, the evolutionary contents are explored using familiar frameworks (such as human diversity, genealogical trees, or classification of well-known species), and are introduced using real stories (NRC 1996). These realistic scenarios allow using the activities further to: (1) teach the role of science and technology in society; (2) demonstrate how evolution knowledge applies to daily situations and needs to be accounted for when making political and individual decisions; (3) promote problem-solving skills; and (4) favor the development of effective citizenship. Finally, these activities can also be used to explore other disciplines, such as arts (students may draw themselves, genealogical trees, or expected and/or observed outcomes), mathematics (counting, measuring, grouping, and graphically representing diversity in the classroom or in populations across time) and linguistics (by promoting the development of oral and written communication skills).

Even though each activity can be used as an independent teaching unit, the order presented bellow corresponds to a learning progression in which the concepts from one activity are used in the next (Figure 1). It starts with two activities about basic concepts - intra-specific diversity and heredity - and is followed by two activities about major evolutionary mechanisms - natural selection and genetic drift. Finally, the learning progression ends with the activity about systematics, allowing students to move from micro to macro evolution, and articulating different topics from the former activities to develop tree-thinking skills.

Intra-specific diversity

The main goal of the 'intra-specific diversity' activity is to help students notice the existence and ubiquity of intra-specific variability. Human diversity is used to achieve such goal, as students are familiar with such conspicuous and abundant diversity. Furthermore, by recognizing human diversity, children may develop a better knowledge of themselves, a competence that is commonly required in elementary school curricula of several countries (Additional file 1). Also, by discovering that numerous human traits display strong variability and by classifying themselves according to these distinct traits, students are expected to develop respectful attitudes towards human differences and to reject any discriminatory behavior (as intended in several official curricula; Additional file 1).

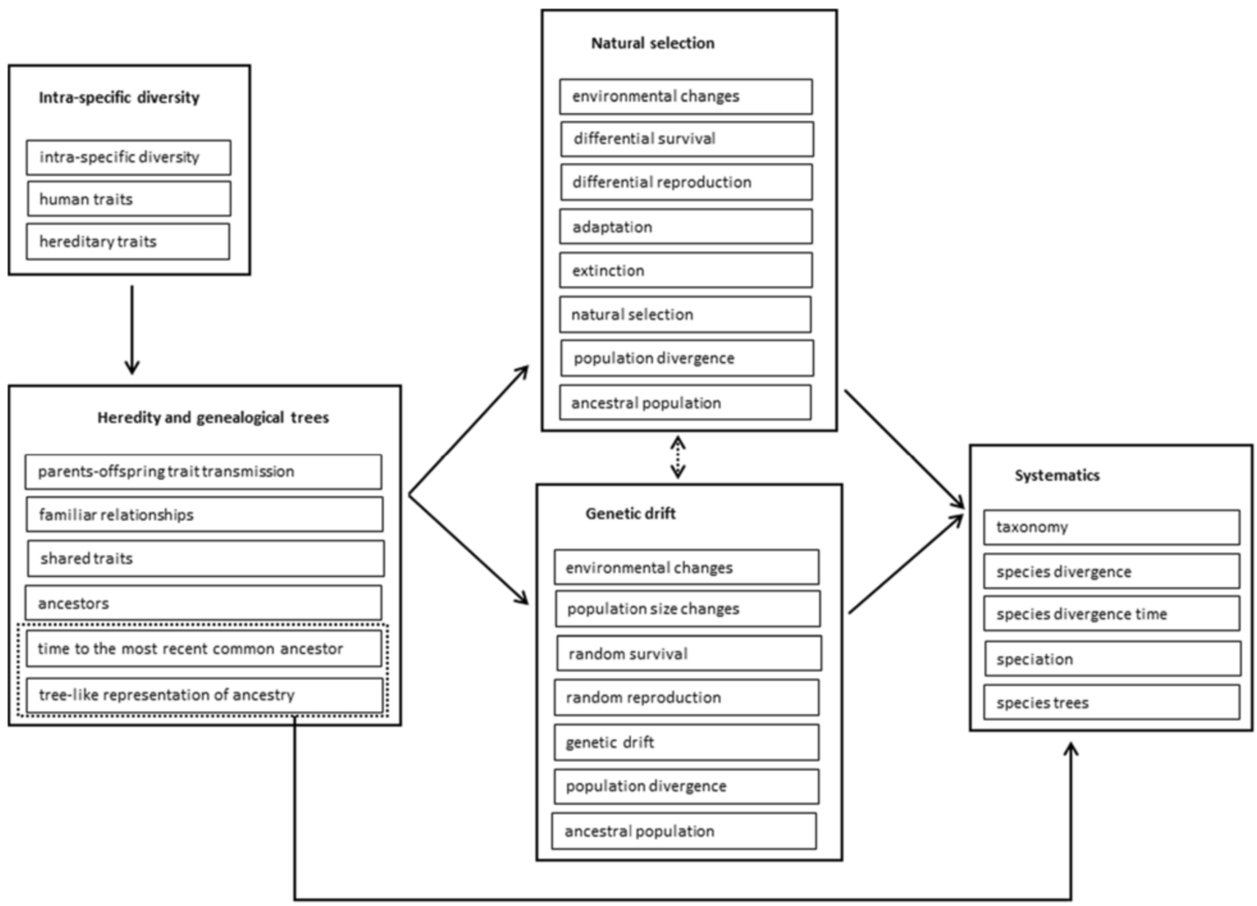
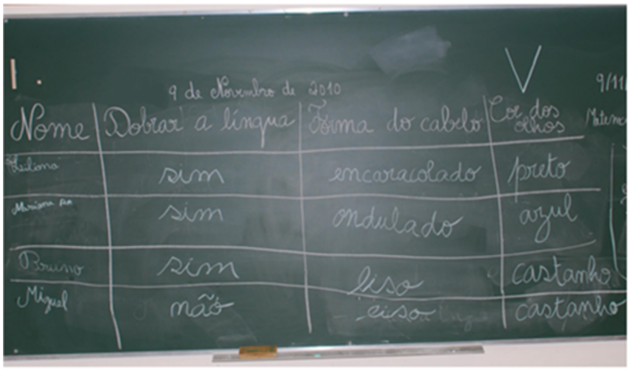


Figure 1 Schematic representation of the learning progression between activities. Each box represents the key concepts learned in each activity and arrows represent how previously learned concepts are integrated in the next activities. All concepts learned in one class are used in all the subsequent classes except those indicated by the dotted lines which are only used on the last one.

Mirrors and measuring tools, such as measuring tapes and/or calipers, are needed for this activity. Magazines with photos of people from different countries and cultures can also be used to enrich the discussion. We started the class by asking students what biodiversity was and discussing with them the existence of three levels of biodiversity: the differences between individuals from the same species (intra-specific diversity), the differences between different species (species diversity), and the differences between species that occur in different habitats (ecosystem diversity). We then asked them if intra-specific diversity was common and to identify variable human features on other students in the class, and to record it on the board (Figure 2A). Then, students were asked to draw themselves taking into consideration these traits (Figure 2B). In all classes students were able to identify variable traits in humans, although in some cases examples of non-biological diversity (such as wearing T-shirts of distinct colors or having painted hair) were also put forward. Some variable traits were pointed out by all the classes (skin, hair, and eye color, for example) while others were less frequently mentioned (such as voice tone or the ability for tongue rolling). We then discussed these features' lists with each class, exploring the concepts of biological *versus* non-biological and inherited *versus* non-inherited variability. After excluding from the list all non-biological and/or non-inherited examples (such as having a scar), we chose among the listed traits one with an obvious continuous distribution (height or skin or hair colors, for example) and two or more with a more discrete distribution (for example, the presence/absence of chin and cheeks dimples or the ability to roll the tongue). For the traits with a discrete distribution, we tried to choose them so that students could be grouped differently according to the two traits. We then asked students to measure these traits in the class using the appropriate tools, to represent the observed variability and to group themselves according to these traits. During this process we asked students how many different groups they could form and what were the criteria used for the inclusion of students in each group. We also explored the concepts of continuous and discrete variability and its implications to classification. Finally,

A



Name	Tongue rolling	Hair shape	Eye color
Liliana	yes	curly	black
Mariana	yes	wavy	blue
Bruno	yes	straight	brown
Miguel	no	straight	brown

B

Figure 2 Main steps of the activity about intra-specific diversity. (A) Discuss with the students examples of biological and inherited human traits and write some of these examples on the board (left: a photograph taken during a class in an elementary school; right: schematic representation of the photograph). **(B)** Ask students to group and represent themselves according to the listed traits.

we discussed the different possibilities for grouping and classifying people (when taking into account distinct traits), giving the same importance to cryptic (such as human blood types, for example) and obvious variable traits (such as skin color). As homework, students were asked to look for the variable traits identified during the class in their close related family (parents, grandparents, brothers and/or sisters, uncles, aunts, and cousins).

To assess the effectiveness of the activity, we asked the students to identify examples of intra-specific biodiversity in other species. All classes were able to identify intra-specific variability in both animal and plant species. As an alternative assessment students may be asked to identify examples of intra-specific diversity among different photos, which may include examples of intra-specific diversity (different people, different dog breads, different roses, and so on), inter-specific diversity (different species of animals and plants), non-biological variability (such as T-shirts of different colors or different cars or dolls), and examples where variability is apparently absent (such as two twin brothers and animal and/or plants from intensive farming where all the individuals look similar).

Heredity and genealogical trees

The ‘heredity and genealogical trees’ activity has two main goals: (1) to help students understanding that many traits are heritable and can be passed through generations; and (2) to introduce students to tree-like representations, and allow them to explore the properties of genealogical trees that are similar to those of a species trees. For this activity, students have to apply concepts explored in the previous activity such as intra-specific diversity and inherited and non-inherited features (Figure 1). Genealogical trees are representations of historical relationships between individuals and have properties that are common to species trees. In fact, species trees can be seen as genealogical trees at large time scales and many models and statistic tools used today to infer species trees are based on genealogical trees (for example, Heled and Drummond 2010). Genealogical trees are often used in Portuguese elementary schools to explore familiar relationships as part of the official programs (Ministério da Educação 2001, 2004), and other countries also include the analysis of familiar relationships and history in their curricula (Additional file 1 and references therein). We propose to further explore these trees with the students so that they can: (1) understand that most of the features of the individuals (such as the ones identified in the previous activity) are inherited from their parents; (2) notice that the vertical axis of genealogical trees represents time; and (3) understand that individuals that share a more recent ancestor are usually more similar to each other than to those with whom they share an older ancestor.

In order to do this, we used the genealogical trees of the students with the phenotypic traits of each family element depicted; an imaginary genealogy can also be used. We explained what a genealogical tree represents and how to interpret the represented information. We then asked them to draw their own genealogical trees (Figure 3A), according to a model tree provided (Figure 3B) using the information of the phenotypic traits of each family member they had previously collected (see the homework suggested in the previous activity). We started to explore their trees asking why they were born with a given set of characteristics. During the following discussion the students analyzed the phenotype of each family element for several traits and realized that the characteristics of one individual are mostly dictated by information coming from their parents.

In our classes we used the analogy of a recipe book to explain hereditary laws to students, and particularly the presence of some features in the children that are absent in both parents. In this analogy each person is constructed according to a recipe book called DNA that contains the information required to construct a given human being (from eye color to blood type). But for each characteristic there are always two recipes, one coming from the father and one from the mother. During gametes' production, parents copy the two recipes but each gamete will carry only one or the other. Since children are familiar with

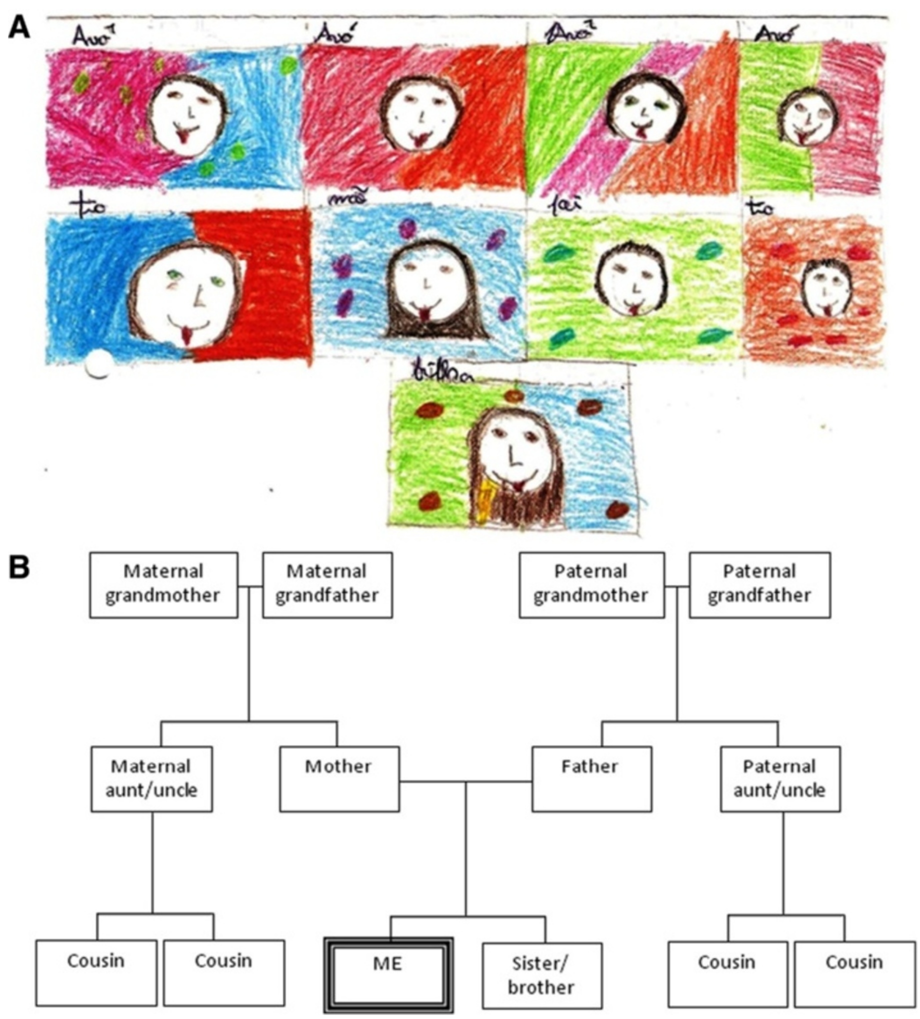


Figure 3 Main steps of the activity about heredity and genealogical trees. (A) Ask students to draw their own genealogical tree using the traits discussed in the activity about intra-specific diversity and the model-tree and ask them why two brothers are in general more similar to each other than to their cousins. **(B)** Representation of the model-tree used by the students.

errors that can be made while copying information, the concept of mutation as a copying error in the DNA can be introduced at this step. When the male and female gametes meet they form an egg that has the two recipes for each of the features required for an individual of a given species to develop. In some cases, one of the recipes that the parents have is not visible but can still be passed onto their offspring. In those cases, it may appear that the children inherited the information from other relatives, such as grandparents.

After discussing the basic principles of parents-to-offspring heredity, we explored the relationships in the genealogy and their relation with time. We started by asking students to identify in the tree who was the person that was born first and last and to draw an arrow indicating the temporal order of births. Then, we asked them who, in general, is more similar (when all the features are taken into account): two brothers or two far-related cousins? Since most students immediately answered that two brothers are, in general, more similar we continued the discussion by asking them to explain why they thought that happens. Students realized that two brothers are usually more similar to each other (that is, they have more features in common) because they share a more recent common ancestors (their parents) than two cousins (whose common ancestors are their grandparents).

As an assessment you may ask the students to write a short text about the history of an imaginary family (either human or non-human), focusing on the characteristics of each of its members and to depict these family members in a genealogical tree. If students learned the main contents, the characteristics of each family member should depend on their parents, family members sharing a more recent common ancestor should be more similar than those sharing older common ancestors, and the family members should be correctly depicted on the genealogical tree.

Natural selection

The goal of the 'natural selection' activity is to demonstrate the mechanism of natural selection, its role on species adaptation to the environment and how it may cause population divergence and ultimately speciation. For this activity, students have to apply concepts such as intra-specific diversity, reproduction, and inheritance that were explored in previous activities (Figure 1).

Although natural selection is not explicitly part of elementary school curricula here considered, this process can be easily explored under several contents such as adaptation, species features and its relation to the environment, energy transfer (trophic chains) and other ecological interactions between species, and the impacts of human activities (Additional file 1 and references therein). In fact, understanding natural selection is essential to promote a deeper and meaningful knowledge regarding many of these subjects. As an example, it is essential that students understand how natural selection acts on existing diversity, to properly realize how some human actions threaten the long-term survival of species by reducing their ability to adapt to environmental changes. Also, teaching students that species' features are usually related with their environment without letting them know the mechanism promoting adaptation may induce and/or further strength misconceptions (such as creationist explanations or the idea that individuals actively try to change to cope with environmental changes; Prinou et al. 2011) that are difficult to correct at later stages (see review in Hermann 2011).

This activity is similar to one described in NAS (1998) but the materials used here are easier to manipulate and more engaging to elementary school students. Engagement is also facilitated by framing the activity within a story in which the students play the role of predators, with evolution happening as a consequence of their performance.

For the activity Smarties (or M&Ms or plastic discs similar to these candies) of five colors (30 of each color), plastic pearls of different colors (including at least two colors identical to two of the colors of the Smarties), and two baskets are needed. Fill one basket with plastic pearls of a color that matches one of the Smarties' colors and the other with plastic pearls of all the colors.

We started the activity by explaining to the students that the basket full of colorful plastic pearls represented a natural and very well-preserved forest where we could still find different species, which would make the environment very diverse and colorful. We then told them that the Smarties represented individuals of a single species with intra-specific variability in external coloration. At this point we asked them for examples of other species showing similar variability and reinforced the fact that all the Smarties belong to the same species. We then told the students that like many other species the Smarties had predators: in this case the students would play the role of Smarties' predators. As in nature, predators would need to hunt the maximum number of preys they could and not waste energy picking things other than their food. Accordingly, to stay alive and play again each student had to pick at least three preys and should not pick plastic pearls.

Before starting the game we asked students to choose six preys of each color, to put them in the basket full of colorful pearls, and to randomly mix everything inside the basket. The predators could then start to hunt: three to four students were allowed to hunt for five seconds each at a time. After this process, the class registered the total number of preys of each color that were hunted (the ones they took from the basket) and that stayed alive (the ones in the basket). We helped students notice that only those that stayed alive could still reproduce. To simulate the process of reproduction each surviving individual of the prey species should have two offspring of the same color (applying the concept of parent-offspring trait transmission) and die. Accordingly, we asked students to calculate the composition of the new generation in terms of colors and to place the corresponding Smarties inside the basket. The predation cycle was repeated as described. After comparing the results, counting the colors that were hunted and that survived, we discussed with students if there was any color that was more hunted or less hunted (the colors of the basket matched all the colors from the prey so students randomly hunted different prey colors) and why that happened. This first step of the activity is equivalent to the genetic drift process; however, at this point it is only intended as an aid for students to be able to formulate hypothesis and explanations for the second step of the activity that focus directly on natural selection.

After the discussion about the results of hunting in a 'natural forest', we told students that an environmental change has occurred (we mostly used the example of fires followed by the rapid colonization of an invasive species as these events are common in Portugal, but other examples such as an agricultural monoculture or the *Biston betularia* history were also effective). This change resulted in a homogenous environment represented by the basket with the plastic pearls of a single color. We re-started the game by placing six preys of each color in this basket and asked students to predict what would happen to the prey species after some generations (Figure 4A; see also the authors' blog Playing Evolution http://playingevolution.blogspot.com). After discussing their predictions we repeated the predation/reproduction cycles as described above (Figure 4B and C) until there was an obvious increase in the frequency of the mimetic color. We discussed with the students the outcome of hunting in this disturbed forest when compared to the 'natural forest': what were the main differences in terms of the total number of prey hunted and their colors and what caused these differences? In all classes, students suggested that the differential survival of colors on the homogenous environment caused a differential reproduction that resulted in the observed differences and we named the process as evolution by natural selection. This discussion was used as an evaluation component. Following it, we asked students what could happen to the population that remained in the homogenous habitat if there was a new environmental change. To make this question clearer we showed students a third basket full with pearls of a single color but different from the color used in the previous 'disturbed habitat' (Figure 4D). In all classes the students immediately answered that the predators would hunt all the individuals of that species which would go extinct. We used this prediction and extended to other types of habitat changes (such as the emergence of a new disease or climatic changes) and other species properties, and discussed how intraspecific diversity of a species affects the probability of its long-term survival.

To further assess the effectiveness of this activity we presented the case of an insular bird species with polymorphism in wing size: some individuals had short wings and were unable to fly while others had long wings, which allowed them to fly. The two types of birds were equally frequent but at some point humans visited the island and accidently introduced cats. The students were asked to predict what humans would found if they return to that island 100 years after that first visit (knowing that each

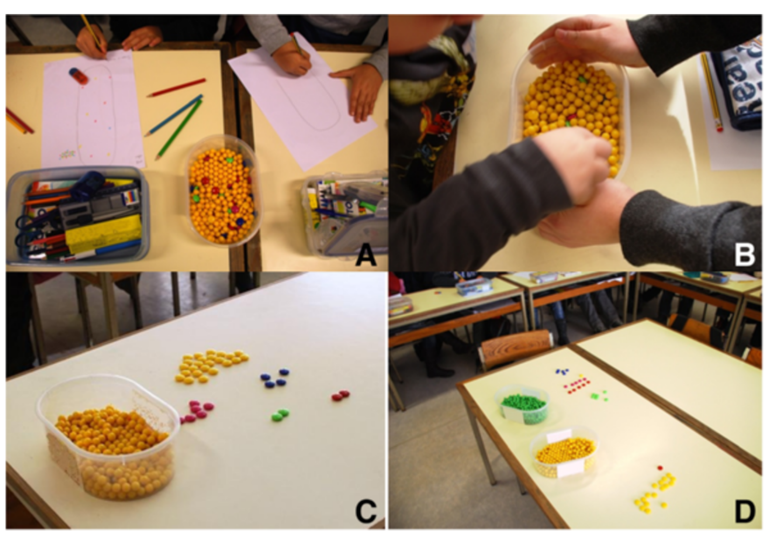


Figure 4 Main steps of the activity about natural selection. (A) Place the same number of Smarties per color on the habitat and ask students to write their hypotheses about what could happen to that population over time. **(B)** Ask students to prey on the Smarties. **(C)** Simulate the reproduction of the surviving Smarties. **(D)** Discuss changes in color frequency (and use other habitat to extend the discussion about long-term viability of a population with low levels of genetic diversity).

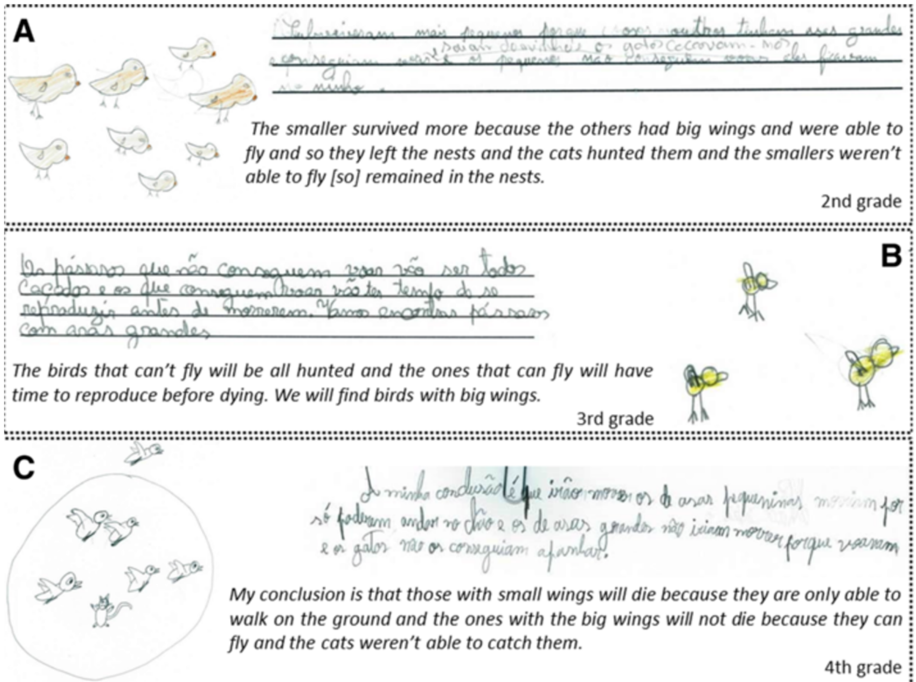


Figure 5 Examples of answers given by students in the assessment of the knowledge about natural selection. When asked about what would happen to an insular bird population with wing-size polymorphism after the release of cats in their islands, most students correctly predicted changes in the frequency of phenotypes, invoking differential survival **(A**, **B**, **C)** and reproduction **(B)** of the more adapted birds.

bird only lives a maximum of 2 years) and to justify their predictions. The majority of students predicted that long wing phenotype would become more frequent and justified this prediction with the increased survival probability of individuals with this phenotype (Figure 5). Three students predicted an increase of short wing frequency but still justified this prediction with an (plausible) increase in the probability of survival of the individuals with this phenotype (Figure 5A).

Genetic drift

The main goal of the 'Genetic drift' activity is to demonstrate the mechanism of genetic drift and how it may impact genetic diversity and cause population evolution and divergence. As for the previous activity, students need to apply concepts that were learned in the two first activities such as intraspecific diversity, reproduction and inheritance (Figure 1). We explored this activity in the context of human impacts on the environment and on the long-term ability of species to survive environmental changes (as a follow-up from the natural selection activity), but it can be explored using other contexts (Additional file 1; see also suggestions below).

For this activity a square cloth, a rectangular cloth, plastic or wood butterflies (or models of any other species, or even regular buttons) of five different colors (30 of each color), and two opaque bags are needed. The butterflies represent one species with intra-specific polymorphism of wing color, the square cloth represents the species' habitat, and the rectangular cloth represents a highway that will cause a habitat disturbance (fragmentation).

We started the activity by asking students if humans could impact intra-specific diversity and how would that happen. During the following discussion, in some classes, students proposed that by reducing the number of individuals, humans could be reducing intra-specific diversity. In these classes the activity was proposed as a possible way of testing this hypothesis. In the classes where this hypothesis has not been proposed we simply asked students what they would expect to happen when species' ranges are reduced by human constructions.

We started the activity placing the cloth on a table and asking students to randomly spread the butterflies in their habitat (Figure 6A; see also the authors' blog Playing Evolution). For the purpose of this activity, we used mimicry as a measure of fitness by noticing that all butterflies had the same fitness in that habitat (that is, no phenotype had an obvious advantage over other). We then told the students that there were two towns in opposite sides of the habitat (which we simulated using toy houses), and that a road was going to be built to connect them, crossing this habitat. We have signalized the location of the two towns so that a straight road would divide the

Figure 6 Main steps of the activity about genetic drift. (A) Randomly spread the same number of butterflies per color on the habitat. **(B)** Place the road and exclude the butterflies that died during its construction; note that there are now two populations and ask students to write their hypotheses about what could happen to those two populations over time. **(C)** Simulate random survival and matting. **(D)** Discuss changes in color frequency in each population.

initial habitat in two areas of very distinct sizes (so that the impact of population size in genetic diversity could be explored). We then asked students to predict what area (the bigger or the smaller) would have higher diversity some years after the road construction and to justify their predictions. Once students registered their predictions, one of them was nominated as the engineer in charge of building the road and asked to simulate the construction by placing the rectangular cloth on top of the square one. During this process, we asked students what would happen

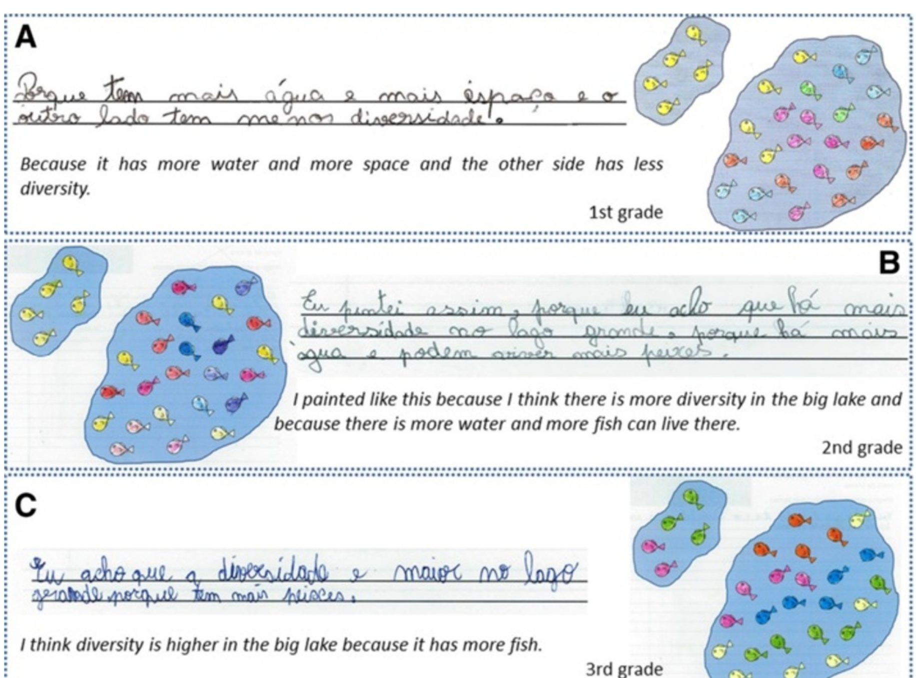


Figure 7 Examples of answers given by students in the assessment of the knowledge about genetic drift. When faced with a situation of a fish population living in a big lake that dried out leaving two lakes harboring two new fish populations with different sizes, most students correctly predicted that the population in the bigger lake would have a higher diversity **(A**, **B**, **C)** although only approximately one-third was able to justify this prediction with the higher number of fish in this lake **(B**, **C)**.

to the butterflies living in the vicinities of the constructions. The students replied these would most probably die and we simulated this by discarding all the butterflies that were covered by the rectangular cloth (Figure 6B). At the end of the road construction we asked the students to describe the differences between the two new populations and between these and the initial one. The students always noticed the differences in population sizes and, when present, the differences in color frequencies and biodiversity. After being asked if there was any explanation for these differences the students told us that these arose by chance.

After writing down the frequencies of the colors on both habitats students simulated random survival and reproduction by placing all butterflies from each habitat in a bag and taking half of them (Figure 6C). We told students that the randomly chosen butterflies were the ones that would reproduce, each leaving two offspring of the same color before dying. This process ensures that the next generation has the same number of butterflies as the previous one. The colors of the new generation in each population were registered and the reproduction cycle was repeated until there was a clear difference in the frequency of the colors between populations. We then discussed the outcomes of the game comparing the result between the larger and the smaller habitats (Figure 6D). Students noticed that smaller populations harbored less variation (in the form of the number of colors present) and that they lost variation more rapidly than larger populations. We also discussed the similarities and differences between genetic drift and natural selection. Students were able to notice that although both mechanisms can lead to changes in frequencies of inherited traits, natural selection increases the frequency of traits that confer an advantage in a given environment while genetic drift is a random process. The direct comparison of this and the previous activity facilitated this conclusion. Finally we discussed how habitat reduction could compromise long-term survival of the species by reducing genetic diversity and thus their ability to adapt in case of environmental changes.

Again, this discussion about the results of the game was used as a first assessment component. We further presented students with two different scenarios that mostly evaluate their ability to relate habitat reduction to the size of a population and their adaptive potential (measured in terms of intra-specific diversity). First we asked students

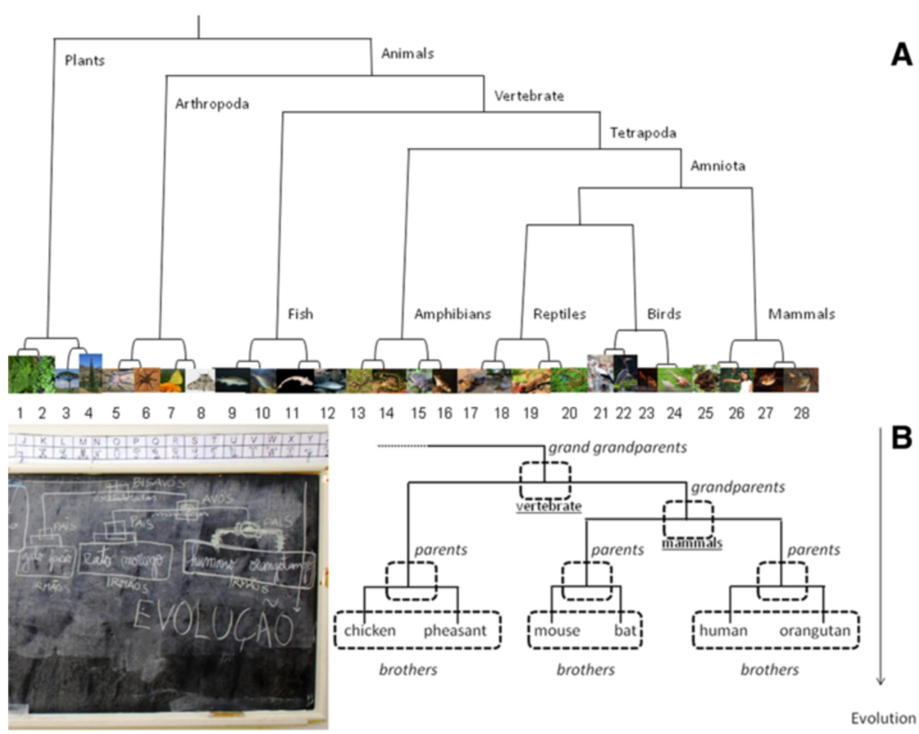


Figure 8 Evolutionary relationship between the species used in the activity about systematic. (A) Evolutionary tree showing the relationship between the species used in the activity about systematic. Note that the figure only depicts some branches of the tree of life and branch lengths are not proportional to time. Numbers correspond to the following species: fern (1), southern maidenhair fern (2), pine (3), fir (4), tarantula (5), spider (6), butterfly (7), moth (8), codfish (9), pouting (10), cat shark (11), shark (12), salamander (13), newt (14), toad (15), Iberian frog (16), turtle (17), chelidae (18), wall lizard (19), lizard (20), stork (21), heron (22), chicken (23), pheasant (24), orangutan (25), human (26), bat (27), and mouse (28). **(B)** Representation of hierarchical grouping of a subset of the species allowing exploring the relation between phylogenetic and genealogical trees (left: a photograph taken during a class in an elementary school; right: schematic representation of the photograph).

what would be the best area for conservation: a unique large area or many smaller regions that, in total, would have approximately the same area as the larger one. After discussing among them, all classes replied that it was better to choose the larger ones as these would preserve more biodiversity that could be important to cope with environmental changes. Second, we presented a case where a previously large river with a very large and diverse fish population dried out almost completely leaving only two lakes of different size. The fish population that survived in the larger lake was bigger than the one that survived in the smaller lake. We then asked students to predict the diversity we expected to observe within each fish population by coloring the individuals and justifying their options. Most students correctly predicted that smaller populations would harbor less genetic diversity than larger ones, although only one-third of the students correctly justified their predictions (Figure 7).

As an alternative, the effects of genetic drift in the genetic composition of a population and the impacts of habitat fragmentation and reduction on species variability can also be studied while exploring plants' growth and ecological requirements (a topic that is part of the official programs in many countries; Additional file 1). For that, a plant species which presents variability in a trait that is easy to observe (such as the famous garden peas used by Mendel that vary in flower color and seeds characteristics) can be used to introduce the activity with a story of forest fragmentation. Ask students to mix the seeds from plants with the distinct phenotypes and to use this mixture to plant vases with distinct areas (two large and several very small vases). Plant many seeds (a minimum of 50) in the larger vases and just a few (10, for example) in the smaller ones. With the students, register the number of seeds planted in each vase. Treat all the vases similarly and make the seeds germinate and grow until it is possible to observe the variable trait. Register and discuss the results with the students as described above.

Systematics

The main goal of the 'systematics' activity is to help students recognize that species diversity and their present features are the result of a long evolutionary history with no predetermined direction (it does not tend to humans), and that historical species kinship can be represented by a tree. This activity also allows students to recognize the large number and diversity of extant species and provides them tools to classify organisms according to their features, a goal that is common to the vast majority of official curricula here analyzed (Additional file 1 and references therein). Activities similar to the present one have already been suggested for exploring evolution in elementary schools, using both extant (Chanet and Lusignan 2009) and extinct species (Wagler 2010). However, we further

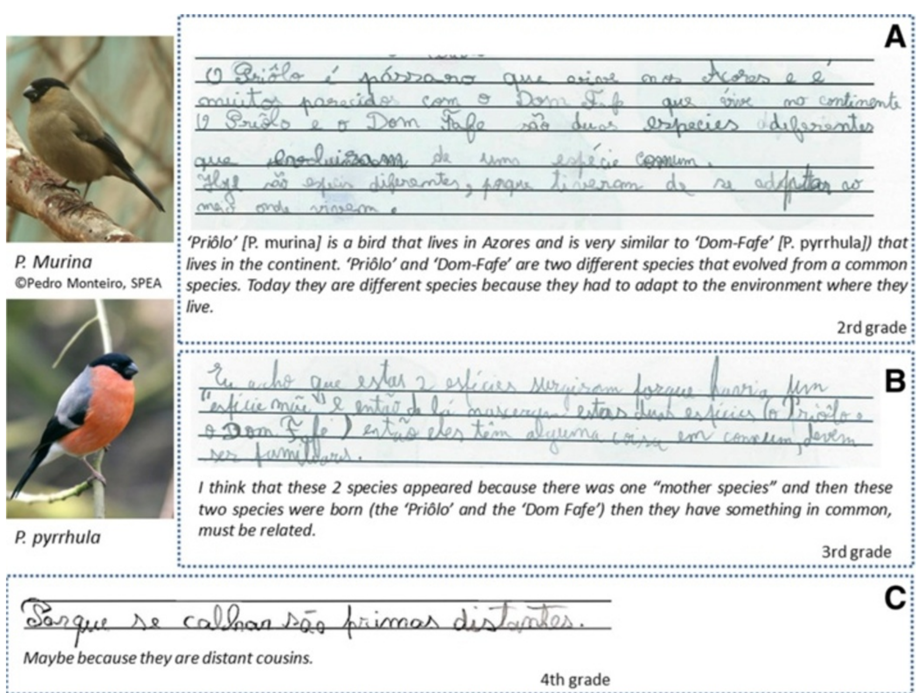


Figure 9 Examples of answers given by students in the assessment of the knowledge about macroevolution. When asked about what could explain the similarities between an insular (the Azores bullfinch, *Pyrrhula murina* (*Priôlo* in Portuguese)) and a continental (the bullfinch, *Pyrrhula pyrrhula* (*Dom-Fafe* in Portuguese)) bird species, more than one-third of the students correctly referred their shared ancestry **(A**, **B**, **C)**.

explore the potential of this activity by making use of the properties of genealogical trees (including the concepts of inheritance or the time to the most recent common ancestor) explored in the second activity here described and by discussing with the students the role of natural selection and genetic drift in the origin of extant species (see concepts workflow in Figure 1).

For this activity we used a set of cards with images of different organisms, chosen to be as familiar to Portuguese students as possible. Beforehand, we collected information regarding the organisms used in the activity, their main characteristics and taxonomic classification (Figure 8A). In class, we started by displaying all cards in a table and asked students to group the species according to their shared characteristics. First, we asked them to make groups of two cards and then, when all cards were grouped in these pairs, to proceed to groups of four and to continue until all cards were grouped either as animals or plants. At each step, we asked students about the criteria they used to make the groups and to write it down. After completing all the groups, we asked the students which were the reasons for this hierarchical grouping. To facilitate the discussion we chose some groups and represented the hierarchical grouping as a tree (Figure 8B). The students immediately recognized the representation as a genealogical tree and this helped them to understand that that tree was a graphical representation of familiar (evolutionary) relationships between species, where descent from a common ancestor was depicted by a branching pattern: species that share a more recent common ancestor group together before grouping with other species. Also, like in the genealogical trees, entities (species in this evolutionary tree and people in genealogical trees) that share a more recent ancestor will have more characteristics in common between them than with other entities. Students were then able to understand that species' characteristics depend on their evolutionary history. We then discussed with the students how natural selection and genetic drift influence species divergence and may cause speciation.

As an assessment of this activity we presented the students two distinct, yet similar, species of birds (*Pyrrhula pyrrhula* and *Pyrrhula murina*) and told them that one species is widespread in Europe while the other is restricted to the Azorean islands. We then asked them how they thought these species originated and why were they similar. More than one third of the students justified the similarities between the two species with their shared ancestry (Figure 9).

Conclusions

Here we present five activities, framed as a learning progression, that allow to introduce biological evolution while teaching science content standards recommended for elementary school in different countries (Additional file 1 and references therein). Since the activities simulate evolution and were always presented as a game framed within a short story, K-4 students are easily engaged into the discussions and are able to understand apparently complex topics such as natural selection and genetic drift. These activities are expected to enhance students' scientific reasoning skills and to provide them the basis for the understanding of life sciences.

Consent

Informed consent was obtained from the patient's guardian for the publication of this report and any accompanying images.

Additional file

Additional file 1: Contents of Official Curricula for elementary schools that can be explored using the described activities.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RC and ASP participated equally in the conception, design and application of the activities, the drafting of the manuscript, and have given final approval of the version to be published.

Authors' information

RC and ASP are postdoctoral researchers at CIBIO/UP with a background on population genetics and adaptation. In the last 3 years both have been also actively involved in evolution outreach, including the conception and implementation of activities that could help students (and the general public) to understand evolution and its relation to other scientific areas.

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