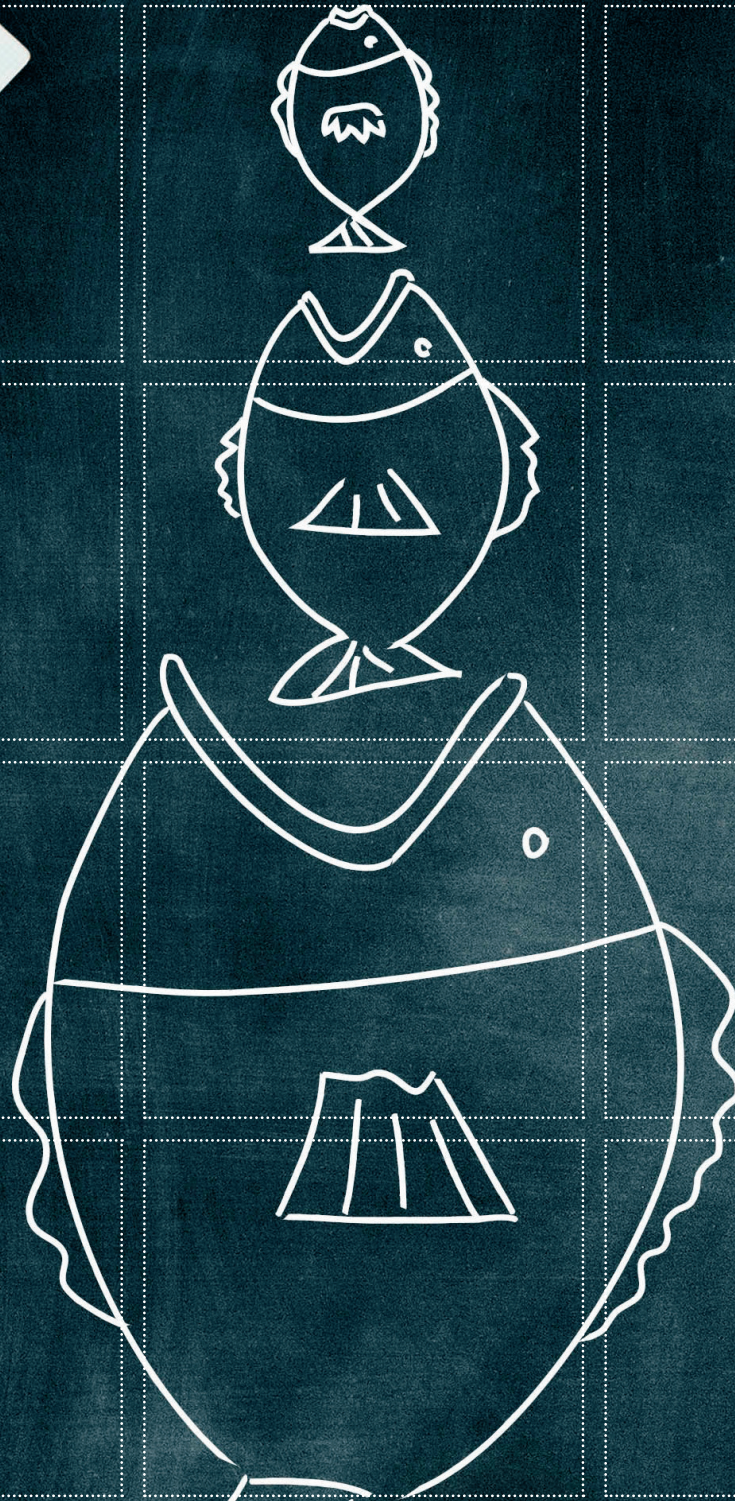


INQUIRY AND ASSESSMENT UNIT



NATURAL SELECTION

Is fitness in the gene or in the animal?

Morten Rask Peterson

NATURAL SELECTION

IS FITNESS IN THE GENE OR IN THE ANIMAL?

Overview

KEY CONTENT/CONCEPTS

- Visualising evolution
- Natural selection
- Genetic drift
- Fitness

LEVEL

- Lower second level
- Upper second level

INQUIRY SKILLS ASSESSED

- Planning investigations
- Forming coherent arguments
- Working collaboratively

ASSESSMENT OF SCIENTIFIC REASONING AND SCIENTIFIC LITERACY

- Scientific reasoning (data entry and observation skills; organisation and interpretation of data)
- Scientific literacy (using physical models to understand adaptation by natural selection; analysis of data and presentation of scientific results)

ASSESSMENT METHODS

- Classroom dialogue
- Teacher observation
- Worksheets
- Student devised materials (report)
- Other assessment items (pre/post test)

Classroom materials for this Inquiry and Assessment Unit are available at WWW.SAILS-PROJECT.EU



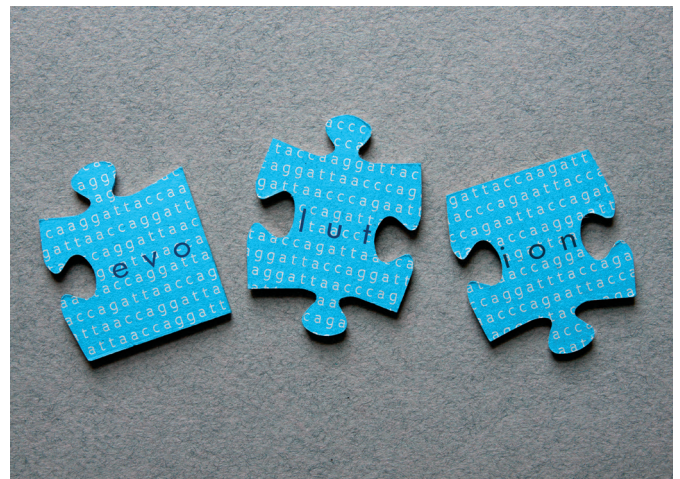
1. INQUIRY AND ASSESSMENT UNIT OUTLINE – NATURAL SELECTION

The **Natural selection** SAILS inquiry and assessment unit focuses on natural selection and the Darwinian theory of evolution, which is part of the biology curriculum at upper second level in most European countries. The topic is addressed in a structured, hands-on activity, during which students simulate a gene pool and the random selection of alleles. They assemble model organisms, called Legorgs, out of Lego® bricks, and measure their fitness. They use this physical simulation to grasp the underpinning concepts of adaptation by natural selection.

The skills developed in this unit include *planning investigations*, *forming coherent arguments* and *working collaboratively*. Skills in *scientific reasoning*, such as collecting data, drawing conclusions are enhanced and students' *scientific literacy* is enriched through comparisons between the physical simulation and the real world. This activity is recommended for implementation at upper second level, where students have sufficient mathematical knowledge to numerically analyse a large quantity of data, and have

conceptual understanding of the biology involved. The assessment methods described in the unit include teacher observation, use of student artefacts and classroom dialogue.

This unit was trialled by teachers in Poland, Hungary, Denmark and Sweden – producing five case studies. In all cases, the teaching approach was *guided inquiry*, although teachers also allowed open inquiry where feasible. Students were aged 14-19 years, with those in Poland and Sweden at lower second level. Skills assessed included *planning investigations*, *working collaboratively*, *scientific reasoning* and *scientific literacy*.



2. IMPLEMENTING THE INQUIRY AND ASSESSMENT UNIT

2.1 Activities for inquiry teaching & learning and their rationale

The **Natural** selection SAILS inquiry and assessment unit details a hands-on simulation activity on natural selection, designed for students aged 15-18 years, in which they investigate multiple genes in Lego® animals (Legorgs). The teaching and learning activities described in this unit were developed by Christensen-Dalsgaard and Kannevorf¹ and adapted for use in the SAILS project. Materials related to the unit activities, including instructional videos, are available online.²

Concept focus	Visualising evolution
Inquiry skill focus	Planning investigations Forming coherent arguments Working collaboratively
Scientific reasoning and literacy	Scientific reasoning (data entry and observation skills; organisation and interpretation of data) Scientific literacy (using physical models to understand adaptation by natural selection; analysis of data and presentation of scientific results)
Assessment methods	Classroom dialogue Teacher observation Worksheets Student devised materials Other assessment items (pre/post test)

Rationale

The title of a very famous article on evolution compressed summarises the importance of this topic in a simple statement: “Nothing in biology makes sense except seen in the light of evolution.”³ Evolution and natural selection are only evident over many generations and so it can be difficult to adopt an inquiry approach to teaching this topic. Computer simulations are often used in classes; however, these can limit students’ understanding of the topic, as they are able to take input and get output, without knowledge of the in-between processes. In this unit the topic is addressed in a hands-on activity, which eliminates this gap in knowledge and describes an inquiry learning activity where students can gain a deeper understanding of the underlying biological concepts, while practicing inquiry skills and competencies at the same time.

Model organisms, called Legorgs, are assembled by the students. The Legorgs consists of six segments – one foot and five segments indicated by different colours of the bricks, representing a gene code with five alleles. Each allele specifies a morphogenetic rule for how the segments (bricks) are placed on the previous segment. This means that the students are working with a physical model including multiple genes making it easier to access concepts like “fitness,” “natural selection” and “genetic drift.” As in every model there are limits and restrictions in the usage and the comparison with the real world. In this particular activity one of the main limitations is that the measurement of “fitness” relies only on one parameter, namely the moving length of the Legorg when falling.

In this activity, three specific concepts are addressed:

- The concept of **natural selection** is the overall conceptual theme of the activity. From this activity, the students can understand that natural selection occurs on the basis of differences between the individuals of a generation. In this activity, random accident, predator-prey, and other negative effects on selection are not addressed. The only parameter for selection is the “fitness” of the individual animal.
- The concept of **fitness** is presented to the students so that they will be able to see that fitness is a concept attached to the whole organism and not to single genes. The students will have the opportunity to see that there is no such thing as a good gene or a bad gene but there are good combinations of genes and bad combinations of genes.
- Students are also introduced to the concept of **genetic drift**, in that they will see genes drifting out of the population and not returning due to the small cohorts in the activity.

Suggested lesson sequence

At the beginning of the lesson, the teacher can provide an introduction to the task that will be performed. This is an opportunity to introduce the scientific terms that will be used in the activity (gene, allele) and demonstrate the connection between the model system (Legorgs) and evolution.

Students are provided with a worksheet, which provides an introduction to the Legorgs and the concept of “fitness” (Figure 1), as well as a table outlining the morphogenetic rules that will be used for assembling the Legorgs (Figure 2). Students may be given some time to become familiar with these rules, and understand how the Legorgs will be assembled.

Once the students are familiar with the task, and how the Legorgs are assembled, they are provided with a workflow diagram and a student worksheet that details how to prepare the first and subsequent generations of Legorgs (Figure 3 and Figure 4).

¹ Evolution in Lego®: A Physical Simulation of Adaptation by Natural Selection, Jakob Christensen-Dalsgaard and Morten Kannevorf, *Evolution: Education and Outreach*, **2009**, 2, 518-526. Available from Springer Link, <http://link.springer.com/article/10.1007%2Fs12052-008-0099-7> [accessed October 2015]

² Home of the Legorgs, <http://www.jcd.biology.sdu.dk/> [accessed October 2015]

³ Nothing in biology makes sense except in the light of evolution, T. Dobzhansky, *The American Biology Teacher*, **1973**, 35, 125-129.

Evolution of Legorgs: a physical simulation of adaptation by natural selection

This activity illustrates adaptation by natural selection for a trait, in this case motility of animals with genetically specified morphology, assembled from six Lego® bricks. The animals are called Legorgs, (short for leg-organisms) since they only consist of a leg.

The individual Legorgs are constructed by random draw from the gene pool of five 8x2 Lego® bricks, each representing a body segment. Each of the bricks can have five colours (alleles), and each colour specifies a morphogenetic rule. The morphogenetic rule specifies how to place the brick on the previous brick (therefore, it is necessary to specify a foot segment, which we by convention always select as black. The motility of the animal is the distance it can move under controlled conditions (see below). We assume that fitness is proportional to the motility, and that individuals transmit genes to the next generation proportional to their fitness. The experiment is to measure the fitness of animals and their descendants through five generations. Our prediction is that in general, fitness should increase with generation.

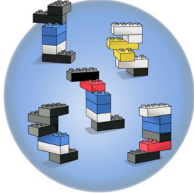


Fig. 1 Fifth-generation Legorgs, with on average 30 mm motility

Scoring fitness.

Legorgs are built from five genes, specifying five segments placed on a foot (Figure 1). The animals are drawn randomly from the gene pools, described below. Each allele (colour) corresponds to a morphogenetic rule, specifying how to place the brick on the previous one, as detailed in the "Morphogenetic rules for assembly of Legorgs." Therefore, the genetic structure will build Legorgs with different morphology. Fitness is scored by assembling the Legorgs (segment 1 is placed on the black foot-segment) and righting them on the foot. When released, the animal may tip and fall, and when righted again it will have moved a certain distance on the surface. The distance moved by a corner of the foot is marked and measured. The average of five measurements is the fitness of the Legorg and is entered in the "Generation of Legorgs" table. For best results let the Legorgs move on a hard, smooth surface such as a glass or whiteboard plate. Here, it is convenient to mark the corner of the foot segment with a whiteboard marker.

Morphogenetic rules for assembly of Legorgs

The morphogenetic rules for assembly of Legorgs are shown below. Legorgs are assembled from segment 1, "counter-clockwise" i.e. the previous segment (grey) is turned counter-clockwise to orient it up-down as in the figures. Segment 1 is placed on the foot that is always black.

Allele/Colour	Description	
Red	Staggered, ahead	
Blue	Just on top	
White	Traverse, right	
Black	Traverse, left	
Yellow	Traverse, middle	

Figure 1: Student worksheet – introduction to the Natural selection SAILS unit tasks

Figure 2: Student worksheet detailing the morphogenetic rules for assembly of Legorgs

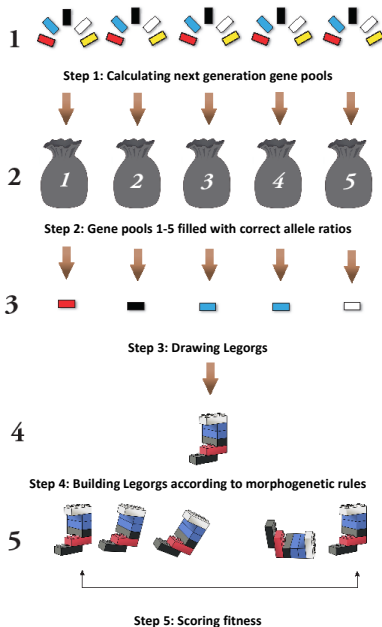


Figure 3: Student worksheet showing the workflow for creating each generation of Legorgs

First generation

For the first generation Legorgs, use the "Generation of Legorgs" table to record the alleles for each Legorg. Each Legorg consists of five genes (bricks) placed on a foot; each of the genes can be one of five alleles (colours).

- Five opaque plastic bags are filled with 5 bricks (1 of each colour in each bag). Each of these bags simulates the gene pool for one of the five genes (in the following generations it is desirable to have 100 bricks in each bag, but it is not necessary in the first generation with equal distribution of alleles).
- Shake bags to ensure randomised draw. Draw a brick from each bag (the sequence is important). Note the sequence of colours drawn on the "Generation of Legorgs" table. When bricks from the five bags are drawn, the animal is specified genetically. Do not construct the animal now, so put the bricks back into the bags (NB!) and select again for the next Legorg.
- Repeat this until you have the genetic structure of 10-20 Legorgs noted on the "Generation of Legorgs" table.
- Now build the Legorgs using the "Morphogenetic rules for assembly of Legorgs," score their fitness and enter fitness value in the final column of the "Generation of Legorgs" table. Calculate and enter the sum and average for fitness for the Legorgs.

Next, the contribution of each individual gene (position of brick with respect to foot) to the overall fitness of the Legorg can be calculated. Each gene is detailed on a copy of the "Gene pool table" – one per gene per generation, i.e. there will be five "Gene pool tables" for the first generation.

- The allele of each Legorg is weighed by their fitness. This is done by entering the fitness of the Legorg (obtained previously) in the table at the position of the allele (colour) for that gene (particular position of the segment relative to the foot).
- Calculate the sum of fitness (Σ fitness) for all Legorgs and the sum of fitness for each allele (Σ colour weight).
- Calculate fitness for each allele relative to the total fitness in percent (rounded to nearest whole number), using the formula $\frac{\Sigma \text{ colour weight}}{\Sigma \text{ fitness}} \times 100$
- The percentage of each allele is simply the number of bricks of each colour needed to fill the gene pool (assuming 100 bricks for the next generation gene pool bag).

Second to fifth generation

- Fill the opaque bags with coloured bricks, according to the calculation from the last generation gene pool table.
- Mutations can be simulated by changing one brick in each of the bags with a brick of another (randomly chosen) colour. This corresponds to an unnaturally high mutation rate, (0,01 against normally 10^{-4} to 10^{-7}), but can probably show effects of mutations during the few generations used here.

As previously, draw the genetic structure of 10 or 20 Legorgs, build, determine fitness and note them in the "Generation of Legorgs" table. After determining fitness of all the Legorgs, transfer the values to the corresponding "Gene pool table" and calculate the next generation gene pools, as performed previously.

Figure 4: Student worksheet detailing the procedure for creating the first and subsequent generations of Legorgs

They are then assigned their first task, to prepare a set of first generation Legorgs (10-20 individuals recommended, although can be adapted based on available resources). They record the alleles for each gene in the first “Generation of Legorgs” table (Figure 5). Students then measure the fitness score for each of the first generation Legorgs, and record the value in the table.

Once the first generation of Legorgs are assembled, and their fitness measured, students need to interpret their results to determine the gene pool for the next generation of Legorgs (Figure 6). Each gene from the previous generation must be assessed individually; therefore students use one gene pool table per gene per generation. Upon analysis of the results, students can calculate the relative fitness (% of allele) and determine the ratio of each allele in the next generation gene pool.

The students should prepare several generations of Legorgs (up to five generations is recommended), as this will allow for sufficient data to be obtained to demonstrate “evolution” of the Legorgs.

If students are engaging well with the task, and understand the correlation between the models and real-world system, it may be interesting to simulate a mutation. This is achieved by replacing one brick in the gene pool bag with another different colour brick. This is an artificially high rate of mutation (1%), but is useful for demonstrating the effect of mutation in the small number of generations prepared in this activity.

Once students have assembled and measured the fitness for five generations of Legorgs, they will have generated a very large quantity of data (5 generation tables and 25 gene pool tables). To aid them in interpreting this data, and relating their results to the topic of natural selection and evolution, a worksheet can be provided (Figure 7).

To further assess students’ understanding of the relationship between the model Legorg system and natural selection a post-implementation test is proposed, such as that shown in Figure 8.

2.2 Assessment of activities for inquiry teaching & learning

In this section we identify some opportunities for the assessment of inquiry skills. Some tools for formative assessment are proposed, aimed at verifying the development of inquiry skills of *planning investigations* and *forming coherent arguments*. This unit also provides a key opportunity to strengthen students’ scientific reasoning capabilities and enrich their *scientific literacy*. Several assessment opportunities have been identified, and some criteria for the assessment are detailed for these skills.

Planning investigations, scientific reasoning, scientific literacy

Throughout this activity, students need to collect meaningful data, organise large volumes of data and analyse data accurately and precisely. The amount of data in this unit is large and the students work with multiple schemes and tables to keep

Generation of Legorgs

Generation No.	Note allele (colour) for each of the 5 genes in the Legorg and measure fitness					
Legorg no.	Gene 1	Gene 2	Gene 3	Gene 4	Gene 5	Fitness
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
Sum of fitness:						
Average fitness:						

Figure 5: Student worksheet – table for recording each generation of Legorgs

Gene pool table

Each individual Legorg can be described within a gene pool table, as shown below. There should be one table per gene per generation.

Generation No.	Alleles					
Gene No.	Note Legorg's fitness in column of the animal's allele (colour)					
Legorg No.	Fitness	Yellow	Red	Black	Blue	White
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
Σ fitness		Σ yellow weight	Σ red weight	Σ black weight	Σ blue weight	Σ white weight
Relative fitness % of each allele						
$\frac{\Sigma \text{ colour weight}}{\Sigma \text{ fitness}} \times 100$						

Note: The sum of fitness (Σ fitness) is calculated from the total fitness values, regardless of colour of the allele. The sum of the weight for each colour (Σ colour weight) is calculated from the sum of each of the entries for that colour's column

Figure 6: Student worksheet: Gene pool table

Questions

1. Sketch the average fitness results in the diagram below:

2. What do your results show?
3. Which elements of the simulation are realistic and which are unrealistic from a biological perspective?
4. Is motility a good measure for fitness?
5. Describe some biological adaptations.
6. How does natural selection affect genetic variation in a population, and when is it beneficial to have large genetic variation instead of "optimised" adaptation?
7. How would a population of e.g. 100 individuals have influenced your gene pools?
8. Why does natural selection not optimise organisms completely?
9. Which optimisations are improbable by the mechanism of natural selections (hint: think of changes in body plan, like extra sets of appendages)?
10. Why can you see an evolution in just 5 generations in this activity, when we only see evolution happening over many generations?

Figure 7: Student worksheet: Questions to aid interpretation of data

track of their experiments. This requires them to organise their data management and data analysis to come to a meaningful result at the end of the activity. Teachers can assess this skill by observing how the students manage to structure their data collection. These processes can be described through written work or documented through work diagrams and flowcharts made by the students. Some criteria for the assessment of this skill are to consider:

- Is there a joint discussion and decision on how to organise this or is it the "leader" of the group that does this in an authoritative way?
- Is the data collection systemised and are the students capable of keeping track of the different schemes and the large amount of similar data?

Forming coherent arguments, scientific reasoning and scientific literacy

There are two key opportunities for evaluation of student skills in *forming coherent arguments* (an aspect of *scientific reasoning*) and *scientific literacy* – forming conclusions and explaining unexpected results.


When forming conclusions, the students' interpretation should be assessed both at the individual level (the Legorg) and at the generation level (the gene pool). There are a lot of calculations involved in getting the results needed to continue and complete the activity. During data collection, students will be aware of the accuracy in taking measurements and the need to repeat measurements in order to improve accuracy. In the same way, they have the possibility of seeing the individual differences in a generation and the expression of a generation mean.

The students complete a large number of tables and calculate the mean for many individual Legorgs during this activity. These results should be interpreted, perhaps through plotting a graph of the mean fitness score for each generation. Students should be able to explain their interpretation of results for both individual Legorgs and for each generation. The teacher can evaluate student skill by considering the following criteria:

- Do the students understand why they have to calculate means of both the individuals and the generations?
- Is there a discussion on the validity of the measurements?
- Do the students discuss uncertainties in the graphical representation of their data analysis?

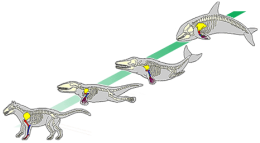
A sample 3-level rubric for assessing students' skills in *forming coherent arguments* is provided in Table 1. The teacher can use these performance levels to assess the group's work. If the teacher observes that a group is at a certain level and do not progress s/he can interact with the group to bring them to a higher level. A top-performing student is capable of generating the necessary data in a consistent manner and can discuss uncertainty of the measurements.

Genetic drift
In November 2010 there was an international meeting on tigers in St. Petersburg, Russia. The purpose was to make a plan for saving the wild tigers. It is estimated that there are about 3000 wild tigers left in the world. Of these approximately 1000 of them are females capable of giving birth to new tigers.



Try to describe what can happen to the genetic variation among wild tigers, when there is such a small population for breeding.

Natural selection
Take a look on the four animals in the figure. Give an explanation on how there can be so many different animal species on Earth



Fitness
The peppered moth has two variations, a light and a dark. In England approx. 97% of all peppered moths were of the light variation before the industrial revolution. After this the picture turned and the ratio turned to having approx. 97% of the dark variant. After the introduction of smoke cleaning and particle filters the population has turned once again so there is again approx. 97% of the light variant and 3% of the dark. Try to give an explanation of this using your knowledge of genetics




Figure 8: Pre- and post-implementation test

Table 1: Rubric for the assessment of the skill of forming coherent arguments

Inquiry skill	Level 1	Level 2	Level 3
Forming coherent arguments	They do the measurements but are not consistent in how they do this for each measurement.	They do the measurements and they take care to do them in the same way throughout the activity.	They do the measurements in the same way throughout the activity and they discuss the validity of and uncertainty associated with the measurements.

A second opportunity for the assessment of students' skill in *forming coherent arguments* is their ability to explain any unexpected results. The students will naturally encounter unexpected results during this activity. The concept of genetic drift is not outlined in the instructions and typically it is not outlined in either the textbooks or in the biology lessons. This means that for most students realising that genes can disappear from a population simply because of natural selection is a new discovery. This new discovery calls for an explanation, and experience with the activity tells us that this is a common start for a discussion of the conceptual understanding of the Darwinian theory.

- Do the students notice the genetic drift of some of the genes?
- Does this lead to any discussions on what happens?
- What explanations do the students give for this?
- Are these explanations discussed in the group for validity?

These questions arise during their work, but the assessment of the students' explanation can be carried out through in-class discussion or evaluation of a student artefact after the lesson.

Scientific literacy

In this unit, students have many opportunities to develop their *scientific literacy*. They can engage in reflective thinking to better understand the processes that they have used, develop their conceptual understanding of the topic of natural selection and transfer the knowledge gained in the model system to real-world situations. At the end of the implementation, students are asked to prepare a final report, which can be used for both formative and summative assessment purposes.

The students can be given a set of questions to answer in their written report, such as those provided in the student worksheet (Figure 7). This report can be an opportunity for reflection on the processes involved in the task, rather than the overall results. The feedback questions for the students' written work should reflect this approach and thereby give the students room for reflection

The students' conceptual understanding could be assessed with a paper and pencil pre- and post-test (Figure 8). The questions in this example are open-ended, meaning that the teachers will have to do a qualitative analysis of the development in conceptual understanding as a result of this inquiry activity. As outlined in the introduction to this unit, the thinking behind natural selection and evolutionary theory is fundamental concept in biology. Understanding this theory therefore opens up for a better understanding of other topics within biology and in interdisciplinary contexts.

3. SYNTHESIS OF CASE STUDIES

This unit was trialled in four countries, producing five case studies of its implementation – **CS1 Poland**, **CS2 Hungary**, **CS3 Denmark**, **CS4 Sweden** and **CS5 Hungary**. In all of the case studies, the teachers had some previous experience of teaching through inquiry. However, the students involved had varying levels of experience of being taught through inquiry.

This unit was recommended for implementation at upper second level, however teachers in **CS1 Poland** and **CS4 Sweden** implemented this with lower second level students, aged 14-16 years. The students in the described case studies were of mixed ability and mixed gender. In **CS1 Poland**, **CS3 Denmark** and **CS4 Sweden**, the students were organised into groups of 4-5 students. In **CS2 Hungary**, the specific study group size is not reported, but the class consisted of five groups of mixed gender and students with dyscalculia were placed in a teacher assigned group. In **CS5 Hungary**, the class consisted of 15 students, but again, group size is not specified. In **CS3 Denmark**, the activity was implemented in either one 180-minute lesson or two 90-minute lessons, while in all other case studies the task was allotted 4-5 lessons of 45-minute duration.

The key skills assessed in the case studies were *forming coherent arguments*, *planning investigations* and *working collaboratively*, while opportunities for the assessment of *scientific reasoning* and *scientific literacy* were also identified. The key assessment method was provision of formative feedback through classroom dialogue, as well as evaluation of student worksheets or student-devised materials.

3.1 Teaching approach

Inquiry approach used

In all cases the inquiry approach used was *guided inquiry*, as detailed in the teaching and learning activities. All groups worked

with the same research question and the same methodology, using the worksheets from the unit or online resources. However, due to the in-built randomness of the task the students got different results from their investigations. Teachers have noted that this activity is quite structured, as the process is outlined step by step in the unit, but that implementation is open as the students have many opportunities to engage in open questioning and interpretation.

Implementation

There were variations in how the unit was delivered in the different contexts. In general, students had received lessons in the biological concepts of natural selection, genetic drift and fitness beforehand. However, in **CS4 Sweden**, the unit was adapted for lower second level students and focused only on natural selection, omitting the concepts of fitness and genetic drift. To commence the lesson, the students watched a video (in Swedish) about evolution.

In all case studies, the students worked in randomly organised or student-selected groups, except for a teacher assigned group of students with dyscalculia in **CS2 Hungary**. There were some differences recorded in terms of group size and how they were organised (Table 2). The group sizes ranged from 3-6 students.

In order to start the activity, the students in **CS1 Poland** started out with translating the material from English to Polish, while using the instructional videos as support for this translation. The teacher reported that this was an opportunity for the students to engage in interdisciplinary studies, as they were learning about scientific concepts in a foreign language. It was also beneficial for the groups to work together in preparation for implementation of the unit.

Table 2: Summary of case studies

Case Study	Duration	Group composition
CS1 Poland	Four lessons (45 min each)	<ul style="list-style-type: none"> Groups of 4-5 students (29 students) Randomly formed; mixed genders
CS2 Hungary	Five lessons (45 min each)	<ul style="list-style-type: none"> Mixed ability and gender One group with students with dyscalculia
CS3 Denmark	One or two lessons (180 min total)	<ul style="list-style-type: none"> Groups of 4-5 students (three separate classes) Teacher assigned; mixed gender and ability
CS4 Sweden	One lesson (60 min)	<ul style="list-style-type: none"> Three separate classes (aged 14-16) Groups of 4-5; students worked individually in one class
CS5 Hungary	Five lessons (45 min each)	<ul style="list-style-type: none"> Groups of 3-4 students Student selected; mixed and single genders

In both **CS1 Poland** and **CS3 Denmark** there was a conceptual pre and post-test on the biological concepts of natural selection, genetic drift and fitness, as suggested in the teaching and learning activities. In **CS1 Poland**, these tests were used in the overall assessment of the students. In **CS3 Denmark** the tests were analysed through a Darwinian landscape model and students who showed positive changes in their understanding of either one of the concepts were invited to a follow-up interview.

In **CS5 Hungary**, the teacher described linking this activity to concepts studied a year earlier (natural selection), and that the activity was incorporated as an aspect of classification of living organisms, that was on the syllabus for the current school year.

In **CS1 Poland**, the teacher described that the students may have had difficulties, as their skill in mathematics was not sufficiently developed at lower second level. In addition, the students in this case study had no prior experience in inquiry-based learning.

Adaptations of the unit

In all case studies, except in **CS3 Denmark** (where the unit was developed), there was a lack of both time and Lego® bricks to carry out the full activity. This resulted in the students investigating fewer than the five generations recommended in the instructions. In **CS1 Poland**, the students worked with cohorts of 3-5 Legorgs, instead of 10-20 individuals per generation as the unit suggests. In this case study, students investigated only one generation (or in rare cases, two generations) of Legorgs.

In **CS2** and **CS5** (both **Hungary**), to overcome the lack of Lego® bricks, coloured cardboard pieces were used when drawing the gene pools for the second and third generations. Again, further generations were not investigated due to lack of resources and time.

In **CS4 Sweden**, the students selected coloured objects from a jar, instead of using Lego® blocks, and inputted the results as colour charts in the original tables from the unit. In one class, they did not assemble Legorgs using Lego® or measure fitness in any way; instead they focused on the selection process. Using this method, students investigated five generations of Legorgs. In another implementation, the students assembled Legorgs and developed a fitness rating scale of “stability” instead of focusing on movement (1 = cannot stand by itself; 5 = stands steady). Students in **CS4 Sweden** also included a computer simulation of the same exercise, using more generations (25) and larger populations. This allowed the study to compare and critique the two model systems.

3.2 Assessment strategies

In the five case studies, many focused on *planning investigations* and *working collaboratively*, as well as *forming coherent arguments* and enhancing *scientific literacy* and *scientific reasoning* capabilities (Table 3). There was a common understanding across all case studies that this activity is particularly good for developing skills in *working collaboratively* and *forming coherent arguments*, although this is only possible if students are given time to work through the activity.

In all case studies, the teachers conducted formative assessment in-class, carrying out on-the-fly evaluations of student performance. In **CS5 Hungary**, the teacher noted that in the initial phase of the activity there was not a lot of time to assess the students, but in the later phase there was time for observation and assessment.

Table 3: Inquiry skills identified by teachers in the case studies

CS1 Poland	<ul style="list-style-type: none"> • Planning investigations • Forming coherent arguments • Scientific reasoning (data entry, drawing conclusions) • Scientific literacy (understand how the model Legorgs relate to evolution; analysis of data and presentation of scientific results)
CS2 Hungary	<ul style="list-style-type: none"> • Planning investigations • Forming coherent arguments • Scientific reasoning (organisation and interpretation of data)
CS3 Denmark	<ul style="list-style-type: none"> • Forming coherent arguments • Working collaboratively
CS4 Sweden	<ul style="list-style-type: none"> • Planning investigations • Scientific reasoning (data entry and observation skills)
CS5 Hungary	<ul style="list-style-type: none"> • Planning investigations • Forming coherent arguments • Working collaboratively (debating with peers)

In **CS1 Poland**, the teacher made use of 3-level rubrics for the assessment of *planning investigations* and carrying out an investigation (Table 4). In addition, the emphasis in the assessment was on *scientific literacy*, which was assessed using an observation sheet to evaluate each student's actions (Table 5). The teacher reviewed how students analysed their data, in particular through use of numerical and statistical methods to obtain well-documented results in order to make judgements on their skills. A total of 15 points were assigned to *scientific literacy*, from a maximum of 30 points. To assess students' skill in *forming coherent arguments*, the teacher assessed their conclusions to ensure that random processes (genetic drift), natural selection and identifying the correlation between the results obtained and real evolutionary processes were all included.

Table 4: Rubric for assessment of inquiry skills in CS1 Poland

Inquiry skill	2 points level	4 points level	6 points level
Adapting the methodology	Student presents the consecutive steps of the natural selection simulation, but without details.	Student creates an action plan of the natural selection simulation with Legorgs, with some guidance from the teacher.	Student creates detailed instructions for the experiment based on the English language instruction films, with a properly detailed description of the consecutive phases, without help from others.
Carrying out an investigation	Group performs measurements, but not always consistently.	Group performs measurements using the same methods sensibly and consistently throughout the activity.	Group performs measurements consistently throughout the activity and can discuss the degree of their reliability and precision.

Table 5: Observation sheet for assessment of students' skill in analysing data

Students' actions	Yes	No	Points
1. Students discuss the experimental layout and data collection method.	X		1
2. The leader decides on his/her solution and does not listen to other group members' ideas.		X	1
3. Students collect data systematically.	X		1
4. The first generation table (illustrating Legorgs gene configuration and their fitness) is laid out properly.	X		1
5. Students adequately fill in the data into the first generation table.	X		2
6. The first generation first gene pool table is laid out properly.	X		1
7. Students adequately fill in the data into the first generation first gene pool table.	X		2
8. The first generation 2nd to 5th gene pool tables are laid out properly.	X		2
9. Students adequately fill in the data into the first generation 2nd to 5th gene pool tables.	X		2
10. Students collect and analyse data for following generations using the same process as the first one.	X		*
11. A graphical representation of results is created.	X		2
* up to 5 bonus points to be earned for active students for this task	Total		15 pts

In **CS2** and **CS5** (both **Hungary**), data collection and data analysis (graphical representation) were the key aspects evaluated for assessment purposes. The teachers provided oral formative assessment in class. In **CS2**, due to a shortage of time, students submitted their responses to a post-implementation questionnaire electronically. The teacher in **CS2** used a 3-level rubric for the assessment of *planning investigations*, *scientific reasoning* and *forming coherent arguments* (Table 6). In **CS5** the teacher used an expanded 4-level rubric to assess *planning investigations*, *forming coherent arguments* and *working collaboratively* (Table 7).

Table 6: Assessment scale used in CS2 Hungary

Assessed skill	Emerging	Developing	Consolidating
Planning investigations Carrying out an investigation	Cannot interpret the tasks without help but manages to do the measurement with some help although not always accurately.	Can interpret the tasks without help, carries out the measurements making sure that they measure in exactly the same way every time.	Quickly understands the tasks, is consistent with measurements and discusses the validity and problems of measurements.
Scientific reasoning (analysis and interpretation)	Identifies sources of error in analysis. Cannot draw conclusions without help.	Identifies sources of error in analysis. Can draw conclusions.	Identifies sources of error in analysis, discusses their effects on results. Formulates conclusions with accuracy and in great detail.
Forming coherent arguments (communication)	Spots unexpected events but cannot account for them.	Spots unexpected events and tries to find an explanation.	Spots unexpected events and can offer an explanation.

Table 7: Assessment scale used in CS5 Hungary

Assessed skill	Emerging	Developing	Consolidating	Extending
Planning investigations Carrying out an investigation	<p>Cannot interpret the task on their own but participates in the planning process and in the implementation with the help of peers.</p> <p>Appreciates the goal and significance of individual steps but cannot properly interpret the activity as a whole.</p> <p>Shows insecurity in measurement, does not notice possible sources of error.</p>	<p>Takes an active role in the planning and implementing process of the task and rectifies mistakes without help.</p> <p>Has a job in the implementation.</p> <p>Understands the goal and procedure of the activity in rough terms but correctly.</p> <p>Spots possible sources of error and attempts to avoid them with some success.</p>	<p>Takes an active role in the planning and implementing process of the task and helps peers when needed.</p> <p>Persistently and reliably works on the implementation. Strives to carry out instructions quickly and accurately.</p> <p>Incorporates measurement error avoidance strategies in the experimental design and works according to the specified protocol.</p>	<p>Quickly and precisely understands the goal and procedure of the activity.</p> <p>Helps and guides peers in planning and implementing process.</p> <p>Can suggest alternatives in order to achieve success.</p> <p>Can create their own alternative protocol if needed to avoid measurement errors.</p>
Forming coherent arguments	<p>Produces data and arguments that are not sufficiently coherent and reliable.</p> <p>Cannot draw conclusions and arguments without help.</p>	<p>Collects and represents data appropriately, can draw conclusions and arguments from them, but the conclusions are not sufficiently coherent.</p>	<p>Collects and represents data appropriately and draws conclusions and arguments coherently and shows precision reflecting on prior knowledge.</p>	<p>Draws conclusions and arguments coherently, in sufficient depth and precision and attempts to find an explanation for unexpected or contradictory results.</p>
Debating with peers	<p>Participates in group work but works with interruptions.</p> <p>Generally participates in group debates as a passive observer.</p>	<p>Participates in group work without interruptions but with varying intensity.</p> <p>Expresses opinions in debates but does not present coherent or persuasive arguments.</p>	<p>Participates in group work actively and without interruption.</p> <p>Actively participates in debates and supports opinions with arguments.</p>	<p>Efficiently organises and assists work and debate of peers. Brings up persuasive arguments for their position in debates, is able to appreciate others' points of views and can be convinced to change their mind if presented with persuasive arguments.</p>

In **CS3 Denmark**, the students handed in a written report based on the follow-up questions in the teaching and learning sequence (Figure 7). During the activity, the teacher gave oral feedback, mainly by posing questions back to the students rather than simply giving them answers. The teachers also used a pre- and post- implementation test (Figure 8) to evaluate the increase in students' understanding of natural selection and evolution after carrying out the inquiry activity. Collected evidence was the students' written reports, interviews with selected students, and video analysis of these students' behaviour during the activity and interview with the teacher.

Students in **CS4 Sweden** developed their skills in *planning investigations* and *scientific reasoning* (data entry and observation). The teachers made their judgements based on observations during the activity, listening to student presentations of results, and evaluation of submitted data tables. The teachers conducted purely formative assessment, as informal feedback was provided during the activity and through whole-class discussions after the activity. The assessment data was not used for summative purposes

3.3 Further developments/extensions

As pointed out in many of the case studies this activity is very time demanding and in all cases was run over several lessons. In one of the case studies it is suggested that the activity could be run in e.g. a volunteer after-school course where the students have the possibility of staying within the activity without having to unpack and pack materials from lesson to lesson and thereby getting a more continuous flow in motivation, knowledge and skills during the activity.

Another extension could be to incorporate the digital simulation more after having run the activity. This would give the possibility for further discussion the impact of the different biological concepts. This discussion could contribute in the development of the skills of debating with peers and *forming coherent arguments*.