



K-12 Partnership Lesson Plan

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BoxCar 2D

Evolving better cars: teaching evolution by natural selection through inquiry

Overview

Students explore how the basic principles of evolution can be used to produce a better vehicle using web-based software. The program, BoxCar2D, allows the user to observe evolution in action with cars in a virtual environment and design vehicles to move over a variety of 2-dimensional landscapes. The program utilizes the basic principles of biological evolution; mutation, reproduction with recombination, and selection (moving faster and farther = higher fitness).

Objectives

At the conclusion of the lesson, students will be able to:

- Understand that evolution happens over generations in populations, not to an individual within its lifetime
- Understand that mutation and recombination create variation
- Understand that although much of the variation is not helpful, some of it is- this random variation allows evolution by natural selection to solve problems in novel and efficient ways
- Understand that evolutionary processes can be used to find innovative solutions to engineering problems

Length of Lesson

This lesson requires two one-hour class periods to complete. The first class period can be used to introduce the website www.boxcar2d.com and the principles of evolution by natural selection. The second class period can be used for independent student inquiry projects. Additional class periods could be added on if students were to present their findings to their classmates.

Grade Levels

6-12

Standards covered (NGSS)

Disciplinary Core Ideas:

Middle School

- **MS-LS3-1:** develop and use a model to describe why structural changes to genes (mutations) located on chromosomes may affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism

- **MS-LS4-4:** construct an explanation based on evidence that describes how genetic variations of traits in a population increase some individual's probability of surviving and reproducing in a specific environment
- **MS-LS4-6:** use mathematical representations to support explanations of how natural selection may lead to increases and decreases of specific traits in populations over time
- **MS-ETS1-2:** evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem
- **MS-ETS1-3:** analyze data from test to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success

High School

- **HS-LS4-2:** construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment
- **HS-LS4-4:** construct an explanation based on evidence for how natural selection leads to adaptation in populations.

Cross Cutting Concepts:

- Patterns
- Cause and effect
- Scale, proportion, and quantity
- Structure and function

Science and Engineering Practices

- Planning and carrying out investigations
- Analyzing and interpreting data
- Constructing explanations and designing solutions

Previous Michigan Standards Met:

- **B5.3:** Natural selection: evolution is the consequence of natural selection, the interactions of (1) the potential for population to increase its numbers, (2) genetic variation of offspring due to mutation and recombination of genes, (3) a finite supply of the resources required for life, and (4) the ensuing selection from environmental pressure of those organisms better able to survive and leave offspring
- **B5.3A:** explain how natural selection acts on individuals, but it is populations that evolve. Relate genetic mutations and genetic variety produced by sexual reproduction to diversity within a given population
- **B4.3C:** give examples of ways in which genetic variation and environmental factors are causes of evolution and diversity of organisms
- **B5.1A:** summarize the major concepts of natural selection (differential survival and reproduction of chance inherited variants, depending on environmental conditions)
- **B5.1B:** describe how natural selection provides a mechanism for evolution
- **B1.1:** scientific inquiry: science is a way of understanding nature. Scientific research may begin by generating new scientific questions that can be answered through replicable scientific investigations that are logically developed and conducted systematically. Scientific conclusions and explanation result from careful analysis of empirical evidence and the use of logical reasoning. Some questions in science are addressed through indirect rather than direct observation, evaluating the consistency of new evidence with results predicted by models of natural processes. Results from investigations are communicated in reports that are scrutinized through a peer review process.
- **B1.1A:** generate new questions that can be investigated in the laboratory or field
- **B1.1B:** evaluate the uncertainties or validity of scientific conclusions using an understanding of sources of measurement error, the challenges of controlling variables, accuracy of data analysis, logic of argument, logic of experimental design, and/or the dependence on underlying assumptions
- **B1.1C:** conduct scientific investigations using appropriate tools and techniques (e.g., selecting an instrument that measures the desired quantity- length, volume, weight, time interval, temperature) with the appropriate level of precision

- **B1.1E:** describe a reason for a given conclusion using evidence from an investigation

Materials

- Set of Legos including wheels, or similar building blocks to make cars
- Hot wheels track, or other materials to make a ramp to test the cars
- Duck tape to mark distance travelled by each car
- Blackboard or whiteboard
- Computers (one for each student or each pair of students)
- Internet connection able to run the program on several computers simultaneously
- Adobe Flash software (free to download)
- Worksheets (found on “BoxCar2D” lesson page on the KBS GK-12 website)

Background

Background on BoxCar 2D

BoxCar2D can be found online at Boxcar2D.com. Developed by Ryan Weber, it uses a physics package that simulates the forces involved in driving a vehicle: the effects of gravity, friction, collisions, motor torque, and spring tension. The website gives more details than this lesson plan for those interested... to learn about the interface, check out the “FAQ” Link (<http://boxcar2d.com/faq.html>); for details on the programming, look at “The Algorithm” link (<http://boxcar2d.com/about.html>).

On the homepage, you can watch a “population” evolve. Each car represents one individual in a population. Each generation these individuals move along the track, and the distance traveled is comparable to fitness. To produce the next generation, a rubric is used to select individuals from the previous generation and “mate” them - it recombines their “traits” and adds mutation to generate “offspring”. Individuals with higher fitness are more likely to be chosen as parents.

The chart on the left side of the page tracks each car’s score, or how far it went on the track (Figure 1a). (If it doesn’t appear, click the “Show” box [Figure 1b], which appears as “Hide” when the scores are visible.) As more generations pass, two lines will appear in the right-hand corner above the track: the red line is the highest performing individual, and the black line is the population mean performance (Figure 1c).

To design a car, click on the “Designer” link at the top of the

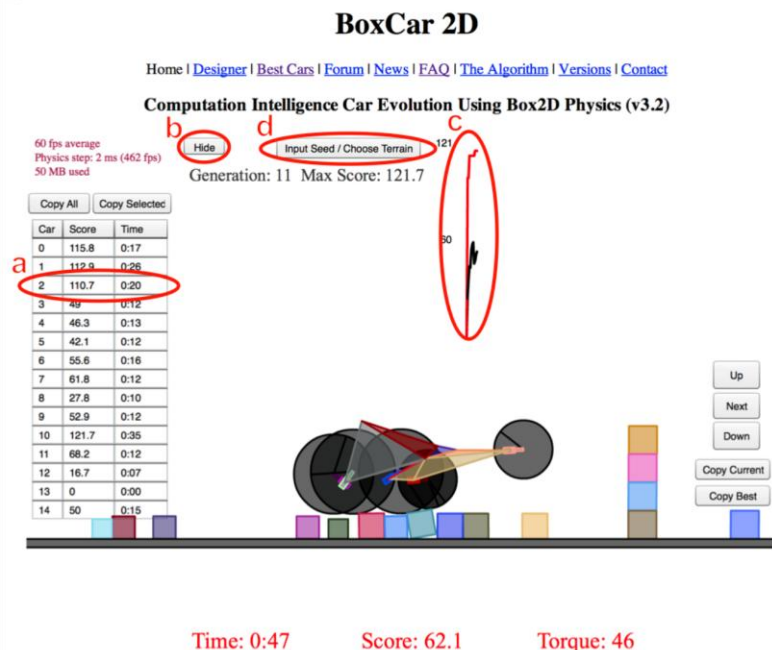


Figure 1: BoxCar2D’s main page. (a) The score for the third car in a population of 20. The score represents the distance travelled along the track. (b) Hides the car scores. (c) Graph showing performance over time – the red line represents the highest scoring car, and the black line shows the population mean score. (d) How to choose a new track type, input a seed car, or start a new random population.

page. The designer page is fairly intuitive; click and drag the triangles (Figure 2a) to change the car design. Color is purely aesthetic, but helps to see exactly what is changing; click on the black boxes to change color. You can manipulate the car body (8 parts, change color, angle, and size of each part) and the wheels (number (0-8), attachment point, and size of each wheel.)

Once you've designed one you like, you can copy it into the program. On the design page, click "copy to clipboard," (Figure 2b) then when you're on the main page where it runs the course, click "Input Seed/Choose Terrain" (Figure 1d). This pops a box up (Figure 3)– it may not be obvious, just a thin black line around the middle of the screen, over where the track appears. Click in the box, you'll see a cursor. Then hit control V to paste your creation– you'll see a bunch of code appear. Now if you hit "input seed car" (Figure 3a) it will start running your creation along with a random assortment of other vehicles – the "population" your car is in.

You can save a car by copying and pasting the code into a document on your hard drive; this can later be pasted back into the BoxCar2D program.

It's possible to copy a single car generated by the program, to be pasted into the Designer page and tweaked or put into a new random population on a different track; highlight the row on the performance table corresponding to that car, click "copy selected," and paste where desired. To transfer an entire population from one track into another, click "Input Seed/Terrain," change the track, and then click cancel.

Other things you can manipulate in the program:

- Population size: (Figure 3c) minimum 2, no max. Larger populations produce more variation on which natural selection can operate, but it takes longer for beneficial mutations to take over.
- Track: (Figure 3d) choose from 10 tracks or let program choose randomly

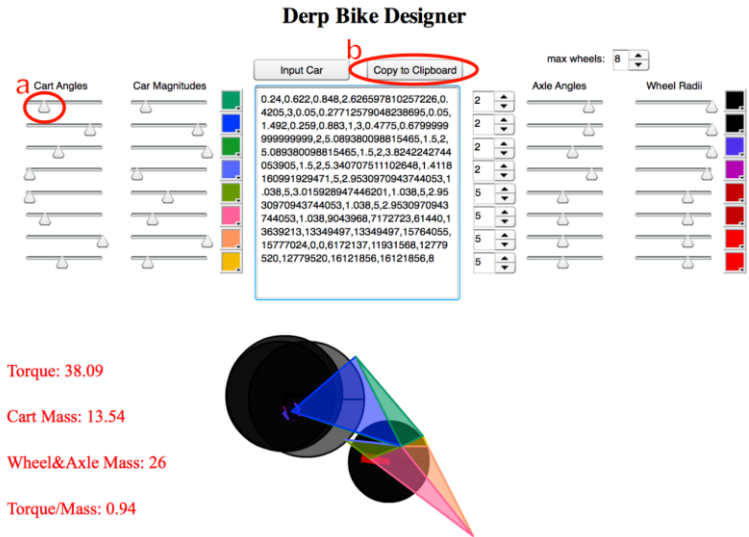


Figure 2: The Designer page on BoxCar2D. (a) Click and drag the triangles to adjust the size and angles of the triangles that make up the car. (b) Click to copy the code that makes up the designed car.

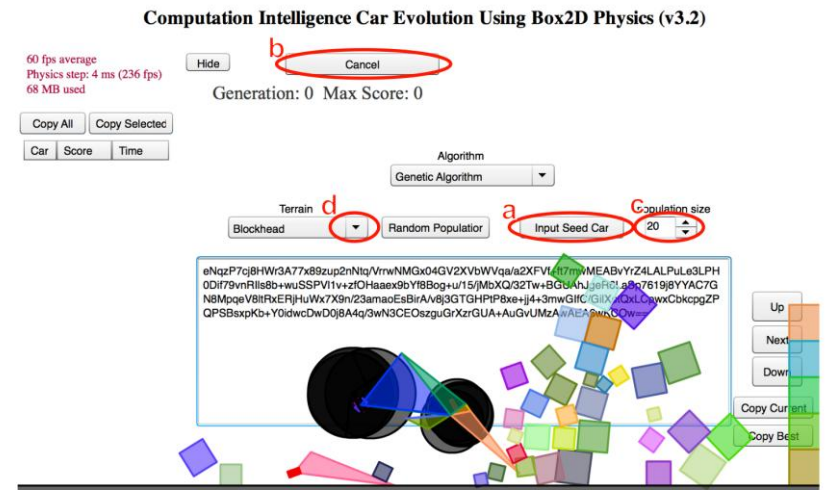


Figure 3: How to input a seed car in BoxCar2D. (a) Click to have the designed car start running on the track. (b) Click cancel to go back to original population without putting in designed car. Can also use to change the track but keep the population. (c) Adjusts population size. (d) Adjusts track.

- Mutation rate: (Figure 1f) a percentage, from 0-100, of how many random variables will change each generation. The higher the mutation rate, the more random variation is introduced – if it is too low, adaptation is limited by a shortage of variation; if it is too high, mutation may eliminate adaptations before they can be established.

Evolution in BoxCar 2D

For the basic lesson plan, use the default population size (20) and mutation rate (5) to keep the focus on adaptation to different tracks. Lessons manipulating the other variables are described briefly in the extensions.

Disclaimer: the following information is for instructors who want a deeper understanding of how the program works, but this level of understanding is not necessary in order to have a good classroom experience.

The program is written using a “genetic algorithm.” The information describing each car is organized into a “chromosome” – a string of code with a “gene”, or section, for each variable (including orientation and size of each car section; attachment point, angle, and radius of each wheel - for an example of a section of the chromosome, see Figure 4). Each “gene” has an inherent color – there is no extra “color gene.” There are a total of up to 40 genes (lower if wheel number is constrained).



Figure 4: Depiction of a portion of a BoxCar's chromosome

The program includes both sources of variation that can fuel evolution: mutation and recombination. Variation is created by mutation, to a user-determined percentage of genes, and/or through recombination between the two selected parents. Recombination happens through a crossing-over process roughly analogous to the biological process in Meiosis I (for students with a deeper understanding of meiosis, similarities are limited by BoxCar2D organisms being essentially haploid – having only one copy of the chromosome.) The program is set to use two-point crossover, which means for each generation one section of the chromosome will be swapped between the parents.

There are two methods (Roulette Wheel and Tournament) that translate fitness (distance travelled along the track) into actual matings and therefore reproductive success. Tournament is recommended for optimal evolution because it is slightly more random, maintaining more variation for long-term evolution. Details of how the methods work are available online.

Activities of the session

LEGO ACTIVITY

1. This lesson uses engineering to show how evolutionary processes can lead to better vehicle performance. Start by setting up a track that Lego cars can run on with a measuring tape next to it on the floor. Challenge the students to build a car that can run the farthest. Give them 30 minutes to build, trial, and rebuild. Be sure each student gets to run their car at least twice (including one rebuild). Then ask them to share what features they included/changed and why - what their process was.
2. After the discussion of the Lego exercise wraps up, ask the students how, instead of the more traditional design approach, they could use what we've been learning about evolution to build a better car. Start by brainstorming what is necessary for evolution to happen. The basics:
 - Variation
 - Some of the variation is passed on to offspring

- Differences in performance connected to that variation
- Some other useful things to come up with:
- Evolution happens in populations
 - Mutation is the ultimate source of variation
 - Crossing over creates variation through making new combinations
3. Then ask them to come up with analogs of these processes in their Lego cars. They could think of all the cars they made as a population. What would a “mutation” be? What would “crossing over” look like in Lego cars? How would you measure their “fitness”? This discussion should be guided to hit the key points listed above, but don’t stifle interesting discussion of solutions other than the ones BoxCar2D uses.
 4. Finally, ask them how long they think it would take to do this with Legos. (They should say a long time!) Can they think of a faster way to do it? BoxCar2D!

BOXCAR2D ACTIVITY

5. Start out with an introduction of the basics of the program described above. Emphasize how the program handles a population, mutation, crossing over, and fitness – contribution to the next generation.
6. Choose two very different tracks from those available on the website. Assign half of the students to each track and start them out watching a random population evolve. They should fill out the first worksheet with observations. *EMPHASIZE THAT THIS POPULATION NEEDS TO BE UP AND RUNNING IN AN OPEN WINDOW FOR THE REST OF THE CLASS - DON.’T TOUCH THAT SCREEN!!* Five minutes is long enough for this step.
7. Once they have an understanding of how the populations run and what natural selection from random variation looks like, have them open a new window (NOT a new tab – BoxCar2D only runs in active tabs, so you have to keep the first population open in its own window to continue its evolution). Introduce them to the “Designer” page and show them how to paste the car into a population. Give them 15 minutes to design a car they think would run well on the same track they’ve been using, doing as many trial runs as they want. Discourage them from clicking on the “Best Cars” link – encourage them to come up with something on their own, which may be more creative and better than the current fad on the website!
8. Once they’ve completed their cars, have them sketch it on their worksheet (and save the code in a Word file, if you want to use it later).
9. Then have them input the car into the program, record the performance score, and let it evolve. They should use the second worksheet to record observations.
10. Let the program run for as long you can, and then have the students sketch their best-running car at the end of evolution. (The highest-performing vehicle from the last generation will always be the first to run each generation).
11. After they’ve had time to watch the hand-designed cars evolve (timing depends on your schedule and the interest level of the class), keep the hand-designed population evolving but turn their attention to the original, random-evolved population. Divide a blackboard into two sides for each track, and have the students draw their best random-evolved car along with its “fitness” (distance traveled) on the board. Discuss. Emphasize that each run of BoxCar2D in a different window is like a completely independent population.
 - Are there trends that arise through the replication – is there one or are there several “types” that seem to be generally successful?
 - How about across track types – what traits make cars successful on track #1? What traits make cars successful on track #2? How are they the same or different?
 - Do you think the information you got from the evolving population could help you hand-design a better car?
 - Can you think of similar traits in nature – ways that evolution has solved the same problem in similar, or very different, ways several times? (If they need to be led, talk about locomotion – swimming, running, flying.) Be sure to specifically use the word convergence.

12. Let them explore different tracks, while keeping their hand-designed population running undisturbed on an open window. When you have 20-30 minutes left, have them return to hand-designed populations and discuss.
 - Can they see the influence of any of their individual cars?
 - When you saw mutations happen in the first generations, were most of them improvements on your model? (In biological evolution, most mutations have negative effects).
 - How were the final best cars similar to and different from their original designs?
 - Did this population come to a similar best model as the ones started with lots of random variation?
 - What do they think might be the fastest way to get the best model?
 - What does this tell us about speciation? If you have the same ancestors but very different selection pressure, what happens? Would you call the final population from these two different tracks different “species”?
13. Finally, introduce them to the competition on the website, showing them pictures of highly successful cars that have been designed and/or evolved. Let them explore whatever they're interested in for the remaining time.

Resources

- www.boxcar2d.com
- BEACON Education website: <http://beacon-center.org/education-outreach/k-12-education/>
- For more background information on evolution, visit <http://evolution.berkeley.edu>
- For the basics of genetics, visits <http://learn.genetics.utah.edu>

Extensions and Modifications

- *Exploring the effects of population size and mutation rate:* have students develop hypotheses and predictions about how these factors will affect evolution, then divide them into high/low groups (or assign a range of values to describe a curve) to test their ideas.
- *Evolutionary trees:* For a longer-running project, have students create their own phylogenetic tree in BoxCar2D: they can let populations run for anything from an hour to a day, copy the best-performing car and move it into multiple different environments (on separate open windows). By saving the code at the time the car was moved, the best-performing car at each node of the phylogeny can be recreated on the Designer page; students could then display phylogenies beside environmental variables, or test their ability to recreate phylogenies correctly from “fossils” – images of cars out of context.
- *Invasiveness:* do some tracks (environments) shape the evolution of cars that perform better over multiple tracks? Have the students make predictions about how populations well adapted to a pair of tracks would perform on the alternate track, and then test them.
- *Student-guided inquiry:* put the students in groups and let them come up with their own questions. These could include any of those mentioned above; a few additional ideas include looking for convergence in populations evolved first on different tracks and then transplanted to the same track, comparing the performance of populations that started with designed cars to completely random ones, transplanting populations adapted to different tracks to see if some tracks make populations “pre-adapted” for others... the possibilities are endless. Emphasize running multiple populations in parallel as replication; this allows students who are familiar with simple statistics to use t-tests on distance traveled to empirically test their predictions.

