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END NOTE

Bringing network science to primary school

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Abstract

Several papers have highlighted the potential of network science to appeal to a younger audience of high school children and provided lesson material on network science for high school children. However, network science also provides a great topic for outreach activities for primary school children. Therefore, this article gives a short summary of an outreach activity on network science for primary school children aged 8–12 years. The material provided in this article contains presentation material for a lesson of approximately 1 hour, including experiments, exercises, and quizzes, which can be used by other scientists interested in popularizing network science. We then discuss the lessons learned from this material.

Keywords: network science, outreach, primary school, Braess paradox, Dijkstra's algorithm, traveling salesman problem

1. Introduction

Network science has proven a highly valuable tool in many fields of applications in the previous years, ranging from social media networks to the brain or epidemic spreading. This wide applicability of networks makes it a highly valuable resource for outreach activities for any audience, as it is virtually always possible to find a networking application that appeals to the intended audience. Several resources for outreach material on network science exist, often focusing at a younger audience. These materials enable other scientists to reach out to, for example, school children in their own neighborhood without much preparatory work. Most existing materials focus on children in high school (Klimm & Maier, 2020; Cramer *et al.*, 2015; Harrington *et al.*, 2013; Sayama *et al.*, 2017). The described outreach events usually consist of a presentation, followed by exercises on various network science-related topics, such as disease spreading or centrality, with pen and paper or even in Python (Klimm & Maier, 2020).

However, network science can be a very suitable topic for primary school children as well. Indeed, network science has several applications in areas close to small children's interests, and graphs are easy to visualize, making it a more tangible topic than many other mathematical topics. However, most existing material for older children often contains more mathematical details than children of primary schools have learned. Indeed, most children at this age have not learned the concept of a variable yet and are not yet able to read and understand even simple equations. Furthermore, the younger age of the participants makes it necessary to stick to shorter lessons, containing more interactive moments than for older children.

This commentary shows that these hurdles are not too difficult to overcome when adjusting the content of such materials and provides lesson material intended for primary school children. These materials form a 1-hour, prepared lesson plan that can be used by other network scientists interested in popularizing their field.

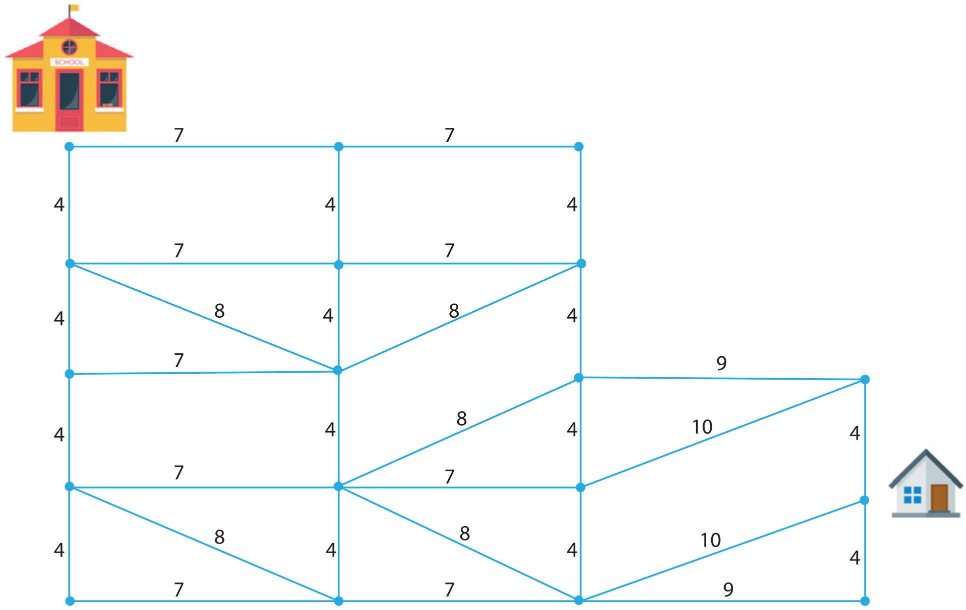

Figure 1. The network on which we applied Dijkstra's algorithm. The left upper building represents the school, and the right bottom building represents home. The numbers next to the roads indicate their lengths. The aim was to find the shortest path from home to school.

In particular, the material was developed for two 1-hour classes at the NEMO Science museum in Amsterdam, the Netherlands. The science museum provides such children's lectures every month, with topics from all sciences. Earlier topics of children's lectures included, for example, the ages of stars in the universe, whether robots can have feelings or how bees cooperate all children aged 8–12 years are welcome at these lectures.

In Section 2, we discuss these materials and the topics we discussed during these classes, and we describe the interactive moments that consisted of exercises, experiments, and quizzes. In Section 3, we evaluate to what extent they were successful or might need further improvements. All material including slides, exercises, and experiments are described in this commentary and are available at (Stegehuis, 2021).

2. Contents

The material focused on choosing the fastest route through a network. To make the topic close to the children's own world, we related the topic to finding the shortest route from your home to your school. We then chose three topics from network science and graph theory that fit well to this topic: Dijkstra's algorithm (how to find the shortest route from home to school from a map?), the Braess' paradox (how to find the shortest route from school to home when there is traffic?), and the traveling salesman problem (how to find the shortest route with intermediate stops?). All three main topics contained some interactive elements, which we will describe below.

2.1 Dijkstra's algorithm

After first explaining the general concept of a network, we provided all children with a network of roads of a city, on which a home and a school were portrayed. All edges in the network were weighted with the length of the road, as in Figure 1. First, all children were asked to find the

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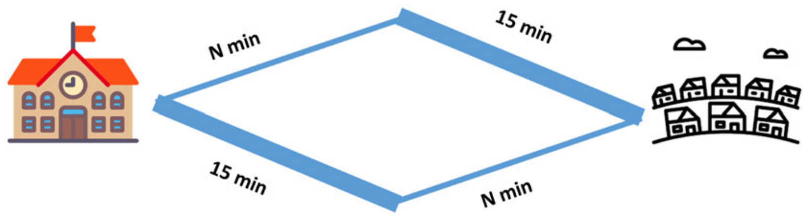

Figure 2. The first network for the Braess' paradox we drew on the ground. The edge weights denote the travel times along the specific road segment. Here, N is the number of cars that take the road segment. Thus, in the upper left road segment, the travel time is equal to the number of cars that pass the segment.

shortest route from school to home by themselves. Afterward, we discussed the results. Who thought they had the shortest route? And how certain were they?

Then, we discussed what algorithms are and together ran Dijkstra's algorithm on pen and paper. We explained the algorithm while going through the steps together. The same map that the children already had was now on a large flipover. Together, we calculated through Dijkstra's algorithm. The children could together look for the vertex on the map with the lowest number so far and circle it with red. Then, we checked the neighbors of this vertex with the lowest value. Finally, we showed an interactive simulation of Dijkstra's algorithm on the Ducth city of Briel (Fitzner, 2021), where one child could choose a destination point, and the simulation ran the algorithm to find the shortest route to it. The children were particularly impressed with this simulation and had many questions on how this could work so fast in an actual computer.

2.2 Braess paradox

The second topic on finding the shortest route was related to the question: "what happens when school gets out, and all children want to go home at the same time?" In other words: how do we choose the shortest way home when there is a possible traffic delay? This relates to the graph-theoretical Braess paradox, where adding more roads can make traffic worse.

To let the children figure this out by themselves, we enacted Braess' paradox live in an experiment. We taped two types of road onto the floor, as shown in Figure 2. As children in this age category usually have not learned the concept of a variable yet, we made the example containing a Braess paradox as simple as possible. For example, whereas typical examples of the Braess paradox make travel times more realistic by having its travel time $10 + N/100$, for example, when 100 cars are there in total, we stuck to just using N as travel time and made the maximal value of N sufficiently small to give easy computations. In this way, we could explain the variable N by just saying that "if eight people choose this road, it will take them eight minutes," and "if two people choose this road, it will take them two minutes." This was something that all children in this age group seemed to comprehend well.

Then, 10 children were invited to enact the Braess paradox live. They were asked to stand in line behind one another. Then, one by one, they could choose one of the two roads and stand still halfway the road so that everyone could see which road they had taken. After all 10 children had chosen the roads, some children in the audience calculated how long the children that took the bottom road had to travel and how long the children that took the top road had to travel. We then asked some children who were enacting the Braess paradox if they would like to make a different choice. For example, if we just calculated that the children that took the top road had to travel for 23 minutes and the others had to travel for 17 minutes, some of the children who took the top road wanted to switch. Then, they could switch roads and children in the audience again calculated how long everyone had to travel. This process continued until all children were satisfied with their choice (so five at the bottom road and five at the top road). In this setting, all children chose a road that took 20 minutes.

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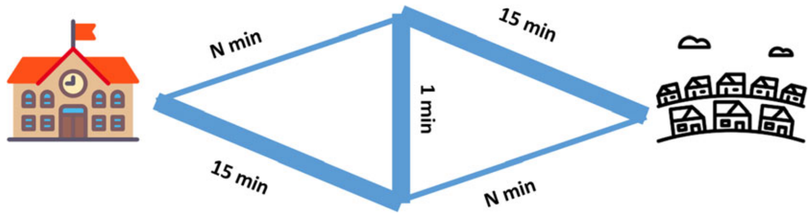

Figure 3. The second network for the Braess' paradox we drew on the ground.

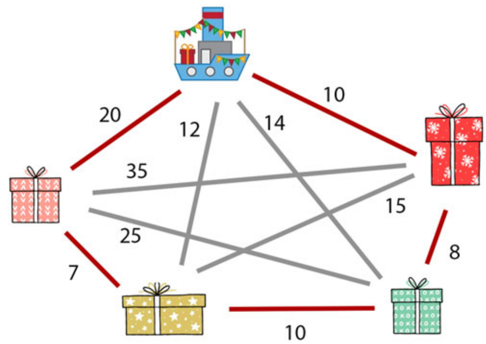

Figure 4. The network example for the traveling salesman example. The goal was to find the shortest route, starting from the boat with the presents, then visiting all houses to deliver the presents. The red route is the shortest one, but how many routes are possible from the boat to these four presents?

After that, we presented the situation where an extra road on the middle was added in the same way (see Figure 3). Children could again pick their favorite road, and afterward we checked if there was a shorter route for them. Now, all children took the N-roads and the new road so that now all children chose a road that took them 21 minutes.

We then discussed why this is weird and how this is possible and showed some examples of the Braess paradox in reality. The concept of the Braess paradox seemed to be quite easy to grasp for some of the children but more difficult for others. However, all children participated very actively in the afterward discussion on what to do with roads that are not necessary for improving traffic.

2.3 Traveling salesman problem

The final topic of the class covered the traveling salesman problem. Here, we related it to the topic of visiting all favorite attractions in a theme park, or Santa Claus having to deliver presents to many homes. We quickly turned to the problem of counting how many possible routes there are to deliver all presents and then return home. There were two quizzes, one asked to compute all possible routes for a small number of nodes, as shown in Figure 4. In this example, the children could actually compute the correct answer of 24. The second quiz was about how many routs exist to visit 20 nodes. Here, most children got very excited, as some very large numbers appeared as options. We then computed together how long a computer that would be able to compute 10^6 such routes in a second would take to compute the length of all possible routes. We ended with the millennium problems of the Clay Mathematics Institute that were introduced at the beginning of the new millennium in 2000[1]. These included seven important unsolved mathematical problems, of which the P versus NP problem is one. The person who solves one of these problems gets awarded one million dollars. For the purpose of this children's lecture, we only stated that by solving the traveling salesman problem or by showing that this is not possible, one million dollars can be won and did not get into the generality of the P versus NP problem.

3. Discussion

In general, the presented topics that are a very small selection of topics from network science proved to be a suitable topic even for young children aged 8–12 years. Even though there is quite some mathematical content behind these topics, the children grasped the meaning of the content quite easily and figured out the answers to most of the interactive questions quite independently.

The children who attended the lecture were extremely enthusiastic and had many questions. In fact, during any moment in the two classes, there was always at least one child with a raised hand, wanting to share something. These questions/remarks were not always related to the content material, but it shows that at this age group, there is a large enthusiasm for learning something new. To be able to still finish in time, we stated at the beginning of the class that children could always raise their hands, but that it would not always be possible to answer all questions during the class, but that children could always ask their questions later. This turned out to be useful, as there were definitely too many questions to cover during the class. An alternative method would be to run such a class with more teachers and discuss children's questions in smaller groups to be able to answer all of them or to discuss them together. Questions that were asked ranged from "Can we use a pen in my favorite color on the flip over now?" to "What if my house is adjacent to a road which is not necessary to improve traffic? How would you then get home?" to "Can we not use drones instead of cars to solve the traveling salesman problem? In that case, we do not need to use roads anymore." These questions led to some small discussions on how this would change the problems we discussed.

The level of the content material seemed to be appropriate for most children who attended the class. The experiment with the Braess paradox went very smoothly, even though at these ages, children have not even learned to concept of a variable yet. Still, when explaining the meaning of the variable N in the Braess paradox, most children quickly saw what the correct result would be, and the experiment only took a few iterations to converge to the correct answer. Some 7-year-old children were also present at one of the classes, and they had more trouble in understanding the material. Still, these children asked many questions and remained active throughout the class. Specifically, the example in Dijkstra's algorithm requires the children to be able to sum several numbers together. In the Dutch educational system, learning how to calculate typically starts at the of age 6 years, which explains why 8-year-olds in this particular setting were better equipped to understand and join in on the part about Dijkstra's algorithm.

Dijkstra's algorithm would probably have been easier to grasp on a smaller network example, but in that case it would have been too easy for the children to find the shortest route by themselves. To make this part of the class quicker, one could do only the first steps together and prepare a second flipover with the finished algorithm on it to show the final results.

Furthermore, the traveling salesman problem could also have been replaced with an application of finding Hamilton tours in a network, where they have to check if there is any tour that passes through all nodes and crosses each edge only once. In application, this could be similar: visiting all attractions of a theme park, while also visiting its beautiful lanes only once. This can be made more tangible also to younger children, by physically giving them a drawing of a network, and some buttons and ropes or so that can be put on the nodes edges. Then, they can remove each node and edge when they visit it, to see whether they are able to go through the entire network or if they get stuck. This is a more tangible exercise than in the current version of the lesson when the traveling salesman problem was covered.

In this particular age group, it is even more important than for high school students to keep them as active as possible, as the attention span of such young children is quite short (Moyer and von Haller Gilmer, 1954; Donnelly & Lambourne, 2011). We therefore started with some jumping around to make it easier for the students to sit still afterward for some time. After the first two topics, we repeated this. This turned out to be quite useful, because after 45 minutes, some children found it difficult to keep concentrated. Other sources of distraction could of course also be used, such as watching a short video, taking a small break or by including a more creative component at that time instead (such as drawing the most beautiful network you can think of) (Geri *et al.*, 2017). Furthermore, we created many small interaction moments, some on topic, and some less so where we discussed what the children knew or thought about the topic in general. Some examples of such questions are in Appendix A, but it is not difficult to generate many more such questions from any given presentation slide.

Finally, this experience leads us to believe that many other network science-related topics can be easily presented to a younger audience as well. Examples close to this topic is the seven bridges of Königsberg by Euler, or Hamiltonian tours or cycles, where it is easy to make small puzzles for children to find such possible tours themselves. Other topics from a different perspective of network science that could be introduced to young children include simple examples of influence maximization. Here, one could show visualizations and include games where one has to draw the network connections such that a process can spread on the network[2]. Other topics include centrality (who is the most important character in a movie) or network visualization. We therefore encourage other mathematicians and network scientists to use and/or adapt this material for their own purposes, or to share their own material, as has often been done with lesson material for older children (Klimm & Maier, 2020; Cramer *et al.*, 2015; Harrington *et al.*, 2013).

Data availability statement. The materials described in this manuscript are available online (see references).

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Competing interests. None.

Notes

1 http://www.claymath.org/millennium. Accessed: 2022-02-16.
2 https://ncase.me/crowds/. 2022-02-16.

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Appendix A. Examples of small interaction questions

These are some examples of small questions that can be used to activate the children throughout the class. Many more possible options for questions can of course also be used.

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- What do you think mathematics is?
- Why could it be important to find the shortest route?
- Which city is pictured here?
- What would you do with a road that turned out to bad for traffic?
- Why could it be important to find the shortest route through many points?
- Do you know the name of these large numbers?

Appendix B. Provided material

The lesson material provided at (Stegehuis, 2021) contains

- Powerpoint slides that were used during the class. The slides themselves do not contain a lot of text, but the comments in the file describe the storyline for all slides in the presentation.
- A pdf of the network that was used to discuss Dijkstra's algorithm that can be printed out for all children to draw their shortest route on.

Additional material needed for the class is

- A flipover (or some other large sheet of paper) with the same network as the one in the pdf file, and colored markers to enact Dijkstra's algorithm together
- Tape or some other material to draw the road networks of Figures 2 and 3 on the ground for the children to walk on.

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