Do People Posses a Global and Ordinal Understanding of Accumulation ? An Experimental Study

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People's seemingly poor ability to understand accumulation principles is well-documented. We argue for a distinction between understanding of the accumulation principle, e.g. how the behaviour of the stock is related to its flows, and application of this information, e.g. solving an accumulation problem where participants need to numerically integrate the flows. Understanding of the accumulation principle contains one necessary and sufficient condition: having a correct representation of the causal relations between the system parts, such an understanding being global and ordinal in nature. In an experimental study with college students, we test this hypothesis by systematically varying two dimensions of how one accumulation problem was presented: (a) type of visual search referring to whether people process the information given in an analytical (local) or holistic (global) manner; and (b) type of information retrieved, referring to whether the information people extract is categorical or ordinal in nature. As expected, we find that a problem format that induces global search enhances people's understanding of accumulation compared to a problem format that induces local search, whilst the ordinal dimension is less significant. Implications for the current debate in the failure to understand stock and flow are discussed.

People´s seemingly poor ability to understand accumulation principles is a well-documented issue. Several studies have shown that people have problems applying the basic accumulation principles correctly, like the relation between inflow, outflow and the level of a stock (Cronin et al,2009). The poor performance in accumulation tasks, i.e., the poor ability to apply accumulation principles to tasks that ask about the relation between inflow, outflow and the level of a stock, has been explained in several ways , yet having problems applying the principles of accumulation does not mean that people do not possess or understand them in the first place.

There is abundant research demonstrating that people fail to apply past learning to new situations that share the same causal or mathematical principles (see Gentner et al, 2009), and when people succeed in accessing an appropriate prior example, then they typically perform well in mapping the solution to the current problem (Pirolli & Anderson, 1985; Reed, 1987, 2012). In this article, we argue for a distinction between understanding of the accumulation principle, e.g. how the behaviour of the stock is related to its flows, and failure to apply this information in certain contexts, i.e. solving a problem in which one has to numerically integrate the flows to get the stock level.

Failure to retrieve and apply information about the relation between two variables for solving a problem, also known as the “inert knowledge” phenomenon, is a major challenge in research on learning, education and conceptual change (Renkl et al, 1996; Barnett & Ceci, 2002; Day & Goldstone, 2012). We posit that people may indeed have an understanding of the accumulation principles, yet, that this information may be “inert”, albeit unused in the tasks that researchers have used in their experiments.

In order to find out if this argument is true, we first need to identify whether and of what nature people possess representations of accumulation principles. In a first experiment we focused on identifying whether 13-year old children posses a basic understanding of accumulation. The focus on children in the pilot study is justified by the importance of identifying and describing the ideas that learners have early in their schooling years, as learners consistently hold ideas that contradict normative scientific principles even after training (Confrey, 1990; Vosniadou & Kyriakopoulou, 2006). We know relatively little about the way children understand accumulation, although there have been a number of researchers in the recent years focusing on children specifically (Zuckerman, 2007; Saldarriaga, 2011). In a second study we refined what we mean by understanding of accumulation principles and add two dimension that we believe are important in distinguishing the nature of accumulation understanding, namely the type of information retrieval and the type of search.

Defining accumulation understanding

In investigating accumulation understanding, most researchers have used graphical tasks, in which participants need to solve a problem based on the extraction of a causal relation between two variables from that graph, referred to as the “department store” task, or the DS task (Pala & Vennix , 2005; Sterman, 2010; Cronin et al, 2009). Cronin and Gonzalez (2007) have pointed out the importance of discovering, on one hand, how people are actually encoding stock and flow problems, and, on the other hand, ruling out the perceptual difficulties related to the interpretation of graphs from the inherent difficulties in understanding stocks and flows. Recently, some authors (Fischer & Degen, 2012 and Hämäläinen et al., 2013) have challenged the use of graphical tasks in assessing understanding about causal relations within the accumulation process, claiming that it is the task design that makes the task difficult to solve. Hämäläinen and his colleagues (2013) draw attention to the wrong cognitive heuristics that might arise from the department store task, whilst Fischer& Degen (2012) argue for a bias in task format that leads to different results when removed. In both cases, giving people a simpler version of the task (Hämäläinen et al., 2013), or simply asking them to explicitly state the relation between the flow and stock (Fischer& Degen, 2012), has led to different, better, results than the initial studies.

To elaborate on the distinction between understanding and application of the accumulation principle, we need a definition. We argue that understanding the accumulation principle contains one necessary and sufficient condition: having a correct representation of the causal relations between the system parts, i.e., the stock and the flows. Correct representation in turn means knowing that "the stock rises if the inflow exceeds the outflow" (Cronin, Gonzalez & Sterman, 2009). Note that this condition is purely qualitative and ordinal in nature. Specifically, understanding refers only to interaction of the system parts, and does not require the problem solver to calculate any numerical outcome of the system. Suffice to say that if an ordinal relationship is established between the two variables, albeit a relationship denoting a certain position in a sequence, then the solution to the problem is known: if inflow is bigger than the outflow, the stock increases. We thus differentiate between information processing, on one hand, which is the cognitive process by which one gets to the understanding of a relation, later described as local or global search, and the type of information retrieved, which can be ordinal or categorical, albeit of or relating to a category. Two consequences arise out of this definition.

First, understanding can clearly be differentiated from application since the latter implies a more complex process. Specifically, solving a graphical task on accumulation as it was used in previous research (e.g. Cronin et al, 2009), requires several steps , i.e. goal formation ("what am I looking for here, what is this a picture of?"), category selection ("I am looking for information about flows"), information extraction ("this line is for the inflow and this other line is for the outflow"), integration ("this is how the inflow relates to the outflow at this time"), and finally, abstraction ("so the principle is: if the inflow is bigger then the outflow, the stock increases") (Guthrie et al, 1993).

The second consequence to arise from the given definition is that, in order to understand the accumulation principle in a given problem, two dimensions are introduced: type of visual search (global vs local) and type of information retrieved (categorical vs ordinal)

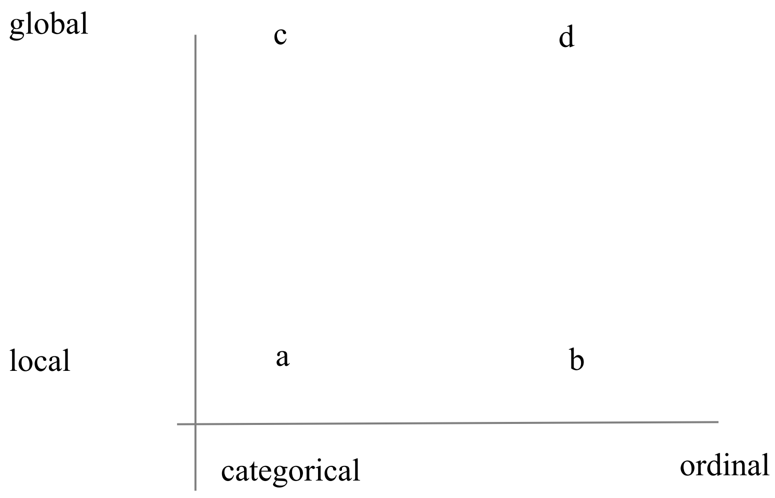

Figure 1. The two dimensions, *type of visual search* and *type of information retrieved* can be combined to make four different types of tasks and problem-solving styles: local-categorical (a), local-ordinal(b), global-categorical (c) and global ordinal (d).

The first dimension, *type of visual search*, refers to whether people search texts or graphs in a *local* or in a *global* manner. With a *local*, data-driven search, people attempt to find specific information within a given set of information, or to identify the highs and lows on a graph; on the other hand, with a *global* search people formulate higher order interpretations, try to get the gist of documents, identify relationships, form a mental model that is useful for problem solving (Wainer, 1992, Mayer, 1992), perceive general trends in a bar graph (*Sanderson et al, 1989*) and extract a rule based on the basic data displayed (Guthrie et al. 1993).

The second dimension, *type of information retrieved*, refers to whether people extract *categorical* or *ordinal* information from texts or graphs. We refer to information as categorical, if it is expressed in natural language, and measured on a categorical scale (e.g., “This bar chart represents the amount of sold cars”). We refer to information as ordinal , if it is expressed on an ordinal scale level (e.g., “The amount of cars sold in March is higher than in April”).This distinction is especially relevant in the case of accumulation, where one basic piece of knowledge that is necessary to understand a simple one stock system is the ability to calculate the difference between inflow and outflow (Saldarriaga, 2011), albeit identify which one is bigger (ordinal information) in order to see whether the stock is increasing, decreasing or staying the same.

Note that both dimensions can refer to both the type of task and the type of visual search participants perform. In most cases, the tasks and visual search will be independent, however, in that different tasks induce different search processes. For example, it was shown that with local questions (“Where is the hammer located?”, “How many American-made cars were sold in June of 1989?”), people form more specific categories, whereas with global questions (“What is the pattern of US vehicle sales over the course of one year?”, “Why is the oval window located in the canter of the ear?”), people form more simple and complex abstractions (Guthrie et al., 1993). We expect a similar connection to exist for the type of information-retrieved dimension, in that categorical (ordinal) questions are more likely to induce categorical (ordinal) responses .

We claim that global (local) search and information retrieved are independent in that any four logically possible combinations can occur (see Figure 1). That is, tasks may be designed to ask for local and categorical information (e.g. «What is the value of emissions around the year 2020?»), for global and categorical («In the following sentences, the two parts of the sentence are logically equivalent . Please fill in the gaps: “CO2 Emissions” is to “CO2 in atmosphere” , as “Savings” is to “…..................”? “CO2 Removal “ is to “CO2 in atmosphere” , as “…...............” is to “Oil reserves”?»), for local and ordinal («In Fig 1, which if the two values around the year 2020 is bigger: emissions or removal?»), and for global and ordinal («What do you think happens to the level of CO2 in the atmosphere if the CO2 emissions level is bigger than the removal?»). Importantly, however, we claim that previous research on SF problems has prompted the subjects with local and categorical tasks. Tasks were designed to lie in this one quadrant, and, as a consequence, this probably also induced a local and categorical visual search in most participants, whilst we claim that the DS task is a global and ordinal one . To test this claim, in our experiment, we used SF tasks from all four quadrants to investigate the effect of the postulated 2-dimensional task design on performance in SF tasks. Since we argue that a global and ordinal search should be more successful for solving SF tasks, we expect solutions rates to vary as a function of tasks so that b > d = a > c.

Pilot experiment

In our pilot study we wanted to see whether children are able to solve simple global accumulation tasks, using examples they are familiar with and they can relate to from their school experience. The learning science literature documents the importance of identifying and describing the ideas that learners have, as learners consistently hold ideas that contradict normative scientific principles even after training (Confrey, 1990; Vosniadou, S., & Kyriakopoulou, N. ,2006). We know very little about the way children understand accumulation, although a number of researchers have started investigating the way children understand and use accumulation in different settings *(*Zuckerman 2007, Saldarriaga, 2011*).*

We tested children´s understanding using global tasks, that is investigating trends and drawing relationship conclusions about accumulation problems. The tasks were either purely verbal, used a bar graph, or used a line graph(see Annex 1). In order to make sure that local search would not interfere with a more global search, we gave the participants a graph literacy test, an adaptation of the test published by Okan et al (2011).

We hypothesized that the majority of children will manage to solve correctly simple, global accumulation tasks.

Method

33 children with ages of 13 and 14 from two international schools in Bergen and Oslo, Norway were asked to complete a series of questions as part of course requirement in Science. They had as much time as they wanted to solve the problems, but no one used more than one hour on the tasks.
The answers were then coded by two independent raters. The interrater-reliability using Cohen's kappa was > .6 .

Results

Between 73 and 92% of children answer correctly questions concerning global accumulation principles, as for instance, changes in a stock depend on its flows.

These results indicate that children have a global, although not numerical, understanding of accumulation, thus providing a richer picture of accumulation understanding than previously presented. To deepen our understanding of this non-numerical distinction influences people´s understanding of accumulation, we performed a second experiment that systematically varied both dimensions, type of visual search and type of information retrieved.

Experiment

Method

In our experiment, we used tasks from all four quadrants to investigate the effect of the postulated 2-dimensional task design on performance in SF tasks.

The participants in this study were 66 university undergraduates from a University of Heidelberg, Germany(info missing about age, and gender).

The tasks were given as a requirement of a course(which course). The tasks consisted of a common part, in which the subjects were introduced to a CO_2 accumulation problem, and then were asked to answer 2 questions. The second question was the same for all the 4 treatments, whilst we varied the first question, which we argue prompts a certain type of visual search, or information type (see the annex for a complete list of tasks). We expected that a global and ordinal prompting task should be more successful for solving a subsequent SF tasks, so we expected solutions rates to vary as a function of this variation, so that

H1: d > b = c > a for the Local/Global dimension

H2: d > c = b > a for the Categorical/Ordinal dimension

where local-categorical is (a), local-ordinal is (b), global-categorical is (c) and global ordinal is (d).

The results are the following:

Dimensions	categorical	ordinal
local	(a)8 correct, 10 incorrect (44% correct)	(b)8 correct, 10 incorrect (44% correct)
global	(c)9 correct, 5 incorrect (64% correct)	(d)11 correct, 5 incorrect (68% correct)

Overall, the results show that the Global and Ordinal group had the highest number of correct vs incorrect answers.

H1: d>b and c>a

On the first hypothesis, we ran a 2 populations z-test for the local-global dimension , and the result was significant (sig.: $z = 1.81$, $p = .035$),

H2: d > c = b > a

The categorical-ordinal dimension did not turn out significant: $z = 0.23$, $p = .41$.

Discussion

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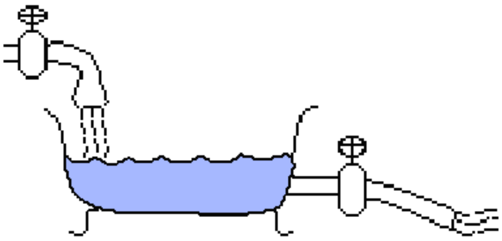
Appendix

Pilot experiment tasks

I. Here you see the image of a bathtub. Water runs into this bathtub through the tap. Meanwhile, water runs out of the bathtub through the drain because it does not seal properly.



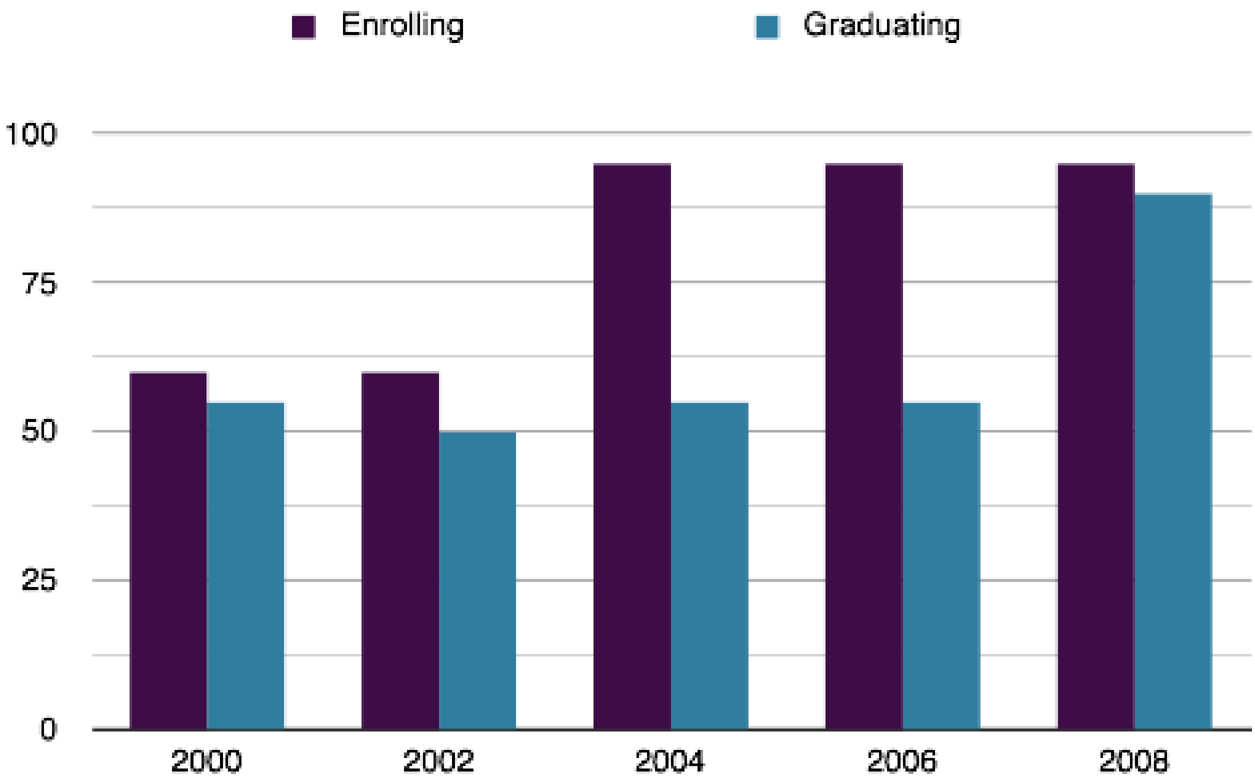
i. What happens to the level of water in the bathtub if more water is running into the bathtub than out of it? Explain!

ii. What happens to the water level if more water is running out of the bathtub than into it? Explain!

iii.What happens to the water level if the same amount of water is running into the bathtub as out of it? Explain!

iv. Imagine, ten minutes ago, you started letting water run into the bathtub and you are now satisfied with the water level. What do you have to do in order to keep the current water level constant? Remember, the bathtub doesn´t seal properly.

II. Every year, the number of students enrolled in the school changes: new students are coming in, whilst others are graduating and leaving the school. The figure below depicts the enrollement and graduating each year in a school for the period 2000-2008.



i.How does the students enrollment compare to graduation between 2000 and 2008 in the figure above? Circle the answer you think is right.

a. More students have been enrolling than graduating
b. Less students have been enrolling than graduating
c. The same number of students have been enrolling and graduating

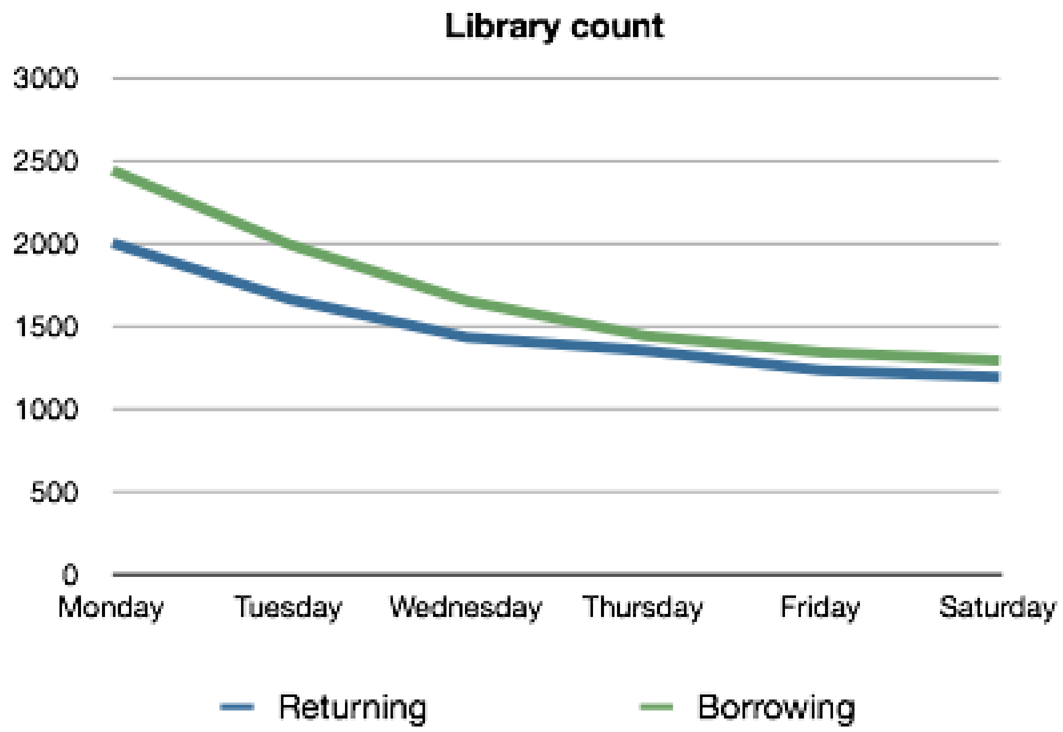
ii. If the student enrollment and graduation has been as depicted in the figure above, what has happened to the total number of students in the school? Circle the answer you think is right.

a. The number of students has risen
b. The number of students has fallen
c. The number of students has remained the same

iii. Let us assume that the principal of that particular school has decided that the total number of students needs to decrease: what does this goal mean for how many students should be enrolled? Circle the answer you think is right.

a. The number of students enrolling would have to be bigger than the number of students graduating
b. The number of students graduating would have to be bigger than the number of students enrolling
c. The number of students graduating would have to be equal to the number of students enrolling.

III. You are a librarian and this week you are part of a project which monitors how many books are in the library at each moment. As people are borrowing books, the number of books is decreasing. The total number increases with people returning their books. The Figure below depicts the borrowing and returning trajectories between Monday and Saturday on that particular week of interest.



i. How does borrowing compare to returning books between Monday and Saturday in the figure above?Circle the answer you think is right.

a. More books have been borrowed than returned
b. Less books have been borrowed than returned
c. The number of books borrowed and returned are equal

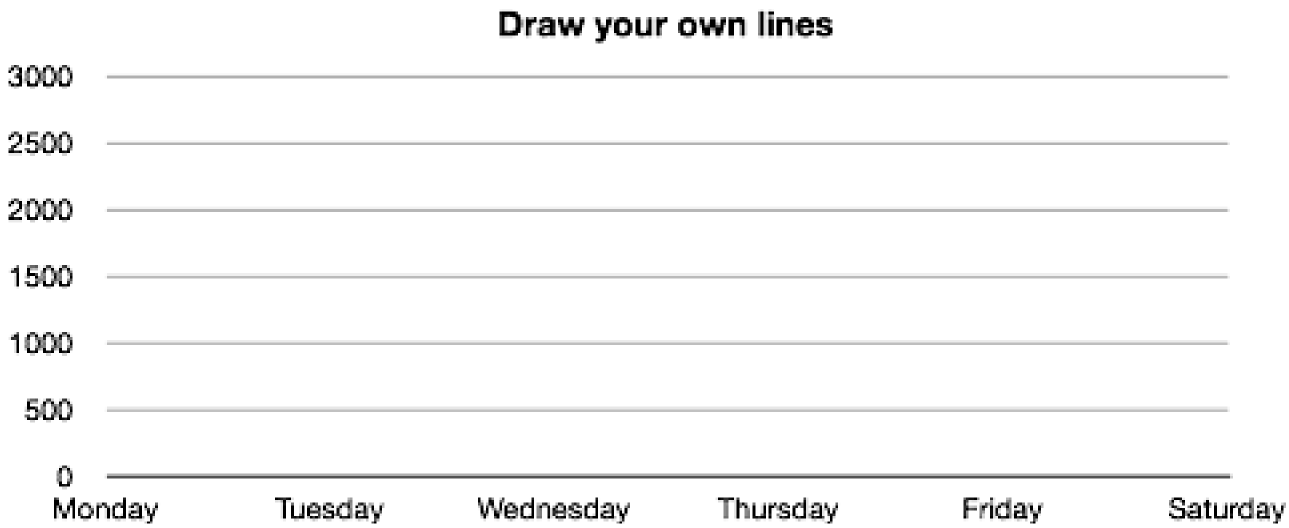
ii. If the books borrowing and returning has been as depicted in the figure above, what has happened to the total number of books in the library? Circle the answer you think is right.

a. The number of books has risen
b. The number of books has fallen
c. The number of books has remained the same

3. If we assume that the number of books needs to increase during the week: what would the corresponding trajectories for the borrowing and returning have to look like in order to attain this goal? Circle the answer you think is right.

a. The number of books borrowed would have to be bigger than the number of books returned
b. The number of books borrowed would have to be smaller than the number of books returned
c. The number of books borrowed would have to be equal to the number of books returned.

4. Please sketch your answer to question 3. into the figure below. Draw one line for borrowing and another line for returning trajectories and label them.



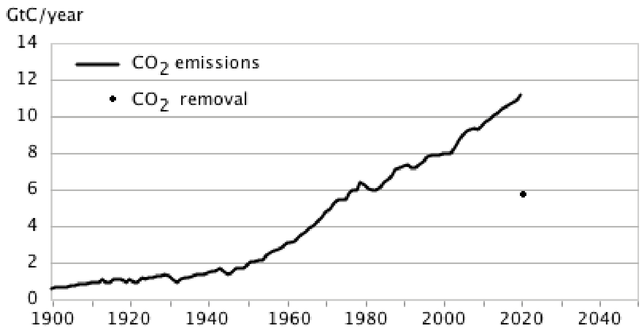
EXPERIMENTAL TASKS

You have been appointed as CHIEF RESEARCHER for solving the world´s climate problem.

The amount of CO2 in the atmosphere, just the contribution from human activity has been increasing in the past 100 years. The more CO2 in the atmosphere, the more will the climate change.

In the graph below you see how world **emissions** of CO2 have developed from the year 1900 and are likely to develop towards 2020.

Assume that the the quantity of CO2 **removed** from the atmosphere by plants and oceans will be 5.9 billion metric tonnes i all years after 2020 (constant).



CO2 emissions

Local/categorical

Question 1: What is the value of emissions around the year 2020?

Question 2 : Assume that the world politicians wish that the amount of CO2 in the atmosphere remain at the same level as in 2020.

What should the world's CO2 emission be after 2020 to make sure that the amount of CO2 in the atmosphere remains at the same level? Think about it, and write down both your work-out (method) and your answer in billion metric tonnes per year(GtC/year).

Local/ordinal

Question 1: In Fig 1, which if the two values around the year 2020 is bigger: emissions or removal?
(Q2: the same as above)

Global/categorical

Question 1: In the following sentences, the two parts of the sentence are logically equivalent (example: "You" are to "your mother", as "your mother" is to "your grandmother"). Please fill in the gaps:

"CO2 Emissions" is to "CO2 in atmosphere" , as "Savings" is to "....................."?
"CO2 Removal " is to "CO2 in atmosphere" , as ".................." is to "Oil reserves"?
(Q2: the same as above)

Global/ordinal

Question 1: What do you think happens to the level of CO2 in the atmosphere if the CO2 emissions level is bigger than the removal?
(Q2: the same as above)