Almost 25 centuries ago, Plato wrote Meno. Meno is the name of a person that engaged in a dialog with Socrates, a dialog which seems to be the first written educational method of humanity, the “Socratic dialog”. At that time it was thought that soul was immortal and, after somebody died, their soul would go to another body. And, in each of their lives, souls would learn a bit more. Talking to Meno, Socrates states that the role of a teacher is not to teach, but to help the student to “extract” from her soul the needed knowledge already learned in previous lives.

To prove his point, Socrates told Meno that he could show that somebody who apparently does not know anything, does actually know something. Meno proposed to use a slave who was with him since his birth and who never went to school. Socrates replied that, if the slave spoke Greek\(^1\), he would be perfect. Meno’s slave (who did not even have a name) interlocked with Socrates in a passionate dialog consisting of 50 questions posed by Socrates and answered by the slave, while drawing in the ground with a stick.

Socrates presented the slave with a 2–by–2 feet square and, after exploring whether the slave knew some basic geometrical notions about squares\(^2\), they agreed that if a square were to duplicate the area of that 2–by–2 square, the resulting square’s area should be eight. At that point, Socrates posed the question that would guide the whole dialog for the first time, question number 10 (Q10): «And now try and tell me the length of the line which forms the side of that double square: this is two feet—what will that be?» He was asking about the length of a side of the second square. And during the fifty questions, the slave went forth and back to finally say that the side of the resulting square would be the diagonal of the original square.

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1. This was mandatory as they needed to communicate.
2. For the complete dialog, please refer to Ref. (Plato, n.d.) or Ref. (Goldin, Pezzati, Battro, & Sigman, 2011).
During the fifty questions, the dialog also explores basic geometrical and mathematical principles that underlay Pythagoras' theorem. For instance, that length and area grow in different proportions (i.e. duplicating the side of a square should quadruply its area) or that irrational numbers exist (i.e. the side of the new square ought to be between 2 and 4 but it is not calculable). A few years ago, Antonio Battro showed this amazing dialog to Mariano Sigman, and we decided to conduct an experiment at the lab to find out if two and a half centuries of education had made an impact on the way our society solves the double-square problem. We would engage twenty-first century free-thinkers in the same dialog that a slave had had with Socrates so long ago.

The original transcription was a smooth dialog that flowed between two persons: Socrates posed a question and the slave answered freely. In an experiment, we could pose one specific question but the subjects could virtually answer anything. Hence, we decided to pilot every question to find all the possible answers that our subjects could give. We then classified those answers as 1) being the same, or 2) being different than the slave's answer. Also, many of the different answers could be mathematically correct or not. For instance, the first time the slave answered Q10, he said that in order to duplicate the area, the side should be duplicated. The slave, guided by Socrates' questions, would then elaborate on this idea until he understood that a side of four would not give an area or eight but of sixteen. If an experimental subject understands more things than the slave, he might say that the side should be smaller than four, which is a correct answer though different than that of the slave.

We then transformed the dialog in an experimental setup as follows: each question included what the experimenter should say while performing an action (where to point, what to draw, etc). Then, the experimenter should compare the subjects' answer to a list of possible responses (obtained as previously explained) and, depending on that, the experimenter would decide which question s/he should pose. If an answer was the same as the one given by the slave3, the experimenter would pose the question that immediately followed. But if a subject's answer was correct and different than the one the slave gave, it was pointless to ask the following question. The experimenter would rather jump to another (predefined) question. For instance, the second time the slave answered Q10, he understood

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3. If two answers involved the exact same concept but used different words, we considered them as being equal (i.e. saying “two”, “twice” or “double”).
that the side should be between 2 and 4 and answered “three” and, after that, the slave explored with Socrates why three is bigger than needed. So, if a subject answered “it has to be less than three” and s/he proved to understand why s/he says so4, the experimenter would jump to the question that Socrates posed after the slave understood that the side ought to be less than three.

Using the script, we conducted all the experiments with each dialog following its own path. The experimenter would play the role of Socrates, “the teacher”, and the experimental subject would play the role of the slave, “the student”. We found a very high agreement between the answers of the illiterate slave and those of our educated subjects (Goldin et al., 2011). As explained before, many of the subjects could skip some of the questions but more than 65% of the questions were answered and, for those, over 90% of the responses were consistent with the slaves’ (and most of the differences resulted from responses that were mathematically correct).

Our first conclusion was that whoever Socrates was, his understanding of the human cognition was outstanding, exceeding times. But we did not stop there. We already knew that after following the dialog, both the slave and all of our subjects succeeded in answering that the side they were looking for was the diagonal of the original square, and they could even point at it5. Furthermore, the last three questions of the dialog (48 to 50) reverberated and reinforced this answer.

If this Socratic dialog is truly educational, it should promote learning. To test this hypothesis, we added a question (Q51) in which we gave our subjects a new square (without explicit size but different from the 2–by–2 one) and posed them the same question that ruled the dialog they had been following for 20 minutes: they had to find the side of a square whose area were the double of that of the new square.

4. If, at any point, an experimenter doubted that the subject understood his/her answer, the experimenter would request the subject to explain his/herself and, if the explanation did not satisfy the experimenter, the answer was not considered correct. In this example, a proper answer for an explanation should be “it should be less than three because three gives a square of nine and we needed a square of eight”. But if in the example the subject answered “less than three because I think so”, the experimenter would go through all the following questions as if the subject had answered “three”.

5. At Q33, the slave seems to quit while answering “I do not know, Socrates”. At that point, Socrates does what he denies: he teaches. He orientates the slave’s attention specifically to the diagonal, which is the answer.
We run all experiments on adults (who had all at least finished high school) and adolescents (who were in high school). Q51 was posed immediately after the answer of Q50, and nobody knew that it was “something special”. Puzzlingly, we found that half of the adolescents and almost one third of the adults could not answer Q51 properly. A lot of the subjects could not generalize that what had happened to the original square would happen to every square, even those that had strictly followed the dialog. The latter suggests that if we had posed Q51 to the slave, he would have failed. Actually, we found a negative correlation between the number of skipped questions and the probability of generalization (i.e. answer Q51 correctly). This insinuates that those subjects that could learn were those that already knew the things that were essential to extract the important information from the dialog, and hence, those that were “more prepared” to really learn what Q50 was originally testing.

We added more evidence to this result in a follow-up experiment looking at what was happening in the brains of the teachers and the students while they were engaged in the dialog.

For the first time, a two–brain educational process was being literally watched (Holper et al., 2013). We explored the hemodynamic response6 of the prefrontal cortex (PFC) of both participants during the whole dialog searching for a neural marker that could help explain the differences between those students that could generalize and those who could not.

After the diagonal argument was exposed for the first time and until the end of the dialog, the PFC activation (measured as increase in oxyhemoglobin concentration, \([O_2Hb]\)) of each student correlated with the \([O_2Hb]\) of the corresponding teacher. Interestingly, the correlation was positive for those dyads whose student would transfer the learned knowledge, and it was negative for the dyads whose students would not generalize it, suggesting that there is a need of some kind of brain synchrony between the student and the teacher for the student to properly learn.

To our surprise, we found that the \([O_2Hb]\) of those students who were not going to answer correctly Q51 was significantly higher (during the dialog) than that of

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6. A wireless device of functional near infrared spectroscopy (fNIRS) located on the skin of the forehead served as an optical method that allowed to calculate the ratio of oxi- and deoxi-hemoglobin and to use it as a measure of cognitive work.
those who were going to generalize. Furthermore, this increase was independent of their teachers, all of whom showed similar PFC activation levels, no matter if their student was going to be able to generalize or not.

If we think about the building of knowledge as the construction, maintenance and growing of brain networks 7, this result can be understood under the light of economy of resources. If a person has the proper background to incorporate a new knowledge to it, then that incorporation will involve less brain activity, it is “cheaper”. But if a person has to learn too many new things, getting to the appropriate level to incorporate knowledge will be more expensive and could not be done to the whole extent. Some things will be learned while others will not.

Educationally speaking, those students who could not apply the new knowledge to any square puzzled us the most. What had they learnt? They did not get to the proper level to apprehend what they were meant to. But for sure, after being immersed in almost the whole dialog, they had learnt something. The “extra” PFC activity shown by those students who could not generalize went in the same direction: their brains were learning so many things that could not handle all. The question now is what those who were not yet prepared to transfer did learn. We are exploring this right now.

7. “Schemas”, may be? Ref. (Tse et al., 2007).
References


As the entomologist chasing butterflies of bright colors, my attention was seeking in the garden of gray matter, those cells of delicate and elegant forms, the mysterious butterflies of the soul, whose fluttering wings would someday –who knows?– enlighten the secret of mental life.

Santiago Ramón y Cajal (1923)