Mother-Son Dialogues:
Light and Vision 1-5

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Science education vs. scientific inquiry: a contradiction

Most educational institutions view the task of science education as disseminating a body of scientific knowledge. They typically do not engage with matters of evidence and arguments that support or refute the propositions presented as "knowledge". Given that scientific" knowledge" is a body of conclusions that the current mainstream scientific community judges to be correct, this practice amounts to instilling among students a body of beliefs that the scientific community takes to be true. This is a form of indoctrination, though it stems from good intentions.

Such indoctrination in science education violates the fundamental principles of scientific inquiry that include an acknowledgement of the fallibility of our conclusions, the doubting and questioning that arise from the awareness of uncertainty, the demand for rational justification, and the understanding of the evidence and argumentation that bears upon knowledge claims and "established" conclusions. One way of remedying this problem is to discard the traditional paradigm of knowledge dissemination and formulate the educator's task as helping learners:

A. understand a body of ***conclusions*** that the scientific community judges to be true beyond reasonable doubt;

B. understand the ***evidence and argumentation*** in support of or against those conclusions (= critical understanding); and

C. develop the capacity for ***critical thinking*** such that they can evaluate the relevant evidence and argumentation, to decide for themselves what to accept, what to reject, and what to keep on hold.

In a system of science education that adopts A-C, it would also be reasonable to proceed further and suggest that we should help the learner:

D. develop the capacity for ***independent inquiry***; and

E. understand the ***epistemology*** of the forms of inquiry that generate scientific conclusions.

To accomplish these goals, it would be eminently desirable to:

F. develop a ***historical perspective*** of the evolution of the conclusions in terms of the *questions* that led to the conclusions, including the relevant factors that led to the changes during their evolution; and

G. become acquainted with the ***leading players*** in that history.

If we accept the paradigm of science education as outlined in A-G, both our classrooms and the learning materials will have to be significantly different from those that are prevalent. The material on light and vision given below is meant to illustrate how the learning resources for science education can incorporate the goals of A-G. It is presented in the form of a discussion in a family that represents a mini-community of scientific inquirers. The standard textbook exposition is replaced by a series of dialogues between a mother and son to mimic the teacher-student *interaction* as much as possible, supplemented with emails from the father that provides for occasional one-sided *exposition*. The dialogues do not have a provision for actual interaction, but the learners may participate vicariously, thereby engaging in the inquiry.

We believe that ***learning resources*** of this kind can accomplish a great deal of A-G, though nothing can replace an educationally enlightened and pedagogically skilled ***teacher*** in the classroom. If, in addition to such learning resources, we also have teachers who can pursue inquiry and critical thinking, we are on the road to scientific inquiry in science education.

Dialogue 1: Empedocles

M: So, how was school today, Rafa?

S: Oh, it was great, mom. Our teacher showed us how to make rainbows with a prism. It was so cool, all the bright rainbow colours, red, orange yellow, green, blue, indigo, violet… I didn't know a prism could change white light into different colours.

M: Does a prism really change white light into lights with different colours? Or does it simply separate the different colours of white light?

S: Huh? What do you mean?

M: Let's see. One possibility is that white light is pure, it is not made of different lights. So what does a prism do? The prism changes part of the white light into red, another part into orange, yet another into yellow, and so on. Another possibility is that white light is not pure, but is made up of different coloured lights. A prism separates the colours of white light into its components, so that you can see each one separately. Which of these possibilities is the right one?

S: Er … I don't know.

M: Did you ask your teacher?

S: No. But come to think of it, Sandy did. I didn't understand what she was saying, but I think I get it now, after what you just said.

M: So, what did the teacher say?

S: He said that white light is composed of different lights, the prism simply separates them, I think.

M: How do you know which of the ideas is true?

S: Mom, you are always asking these impossible questions. My teacher tells us what is true. He wouldn't tell us what's not true.

M: May be he doesn't. But isn't it important for you to figure out for yourself whether something is true?

S: But the teacher says what's there in the textbook. So it must be true.

M: So, everything that a textbook says is true? Rafa!

S: Okay, okay, textbooks are not God's truth. I know, I know.

M: So how do you know that white light is made up of different coloured lights?

S: How will I find out? I don't even know how to begin.

M: May be we should begin with Empedocles and Euclid.

S: Empi who? I know who Euclid is, but who is the other guy?

M: A Greek philosopher. He lived in Sicily about 2500 years ago, in the 5^{th} century BCE.

S: A philosopher? Mom, we are talking about light in the science class. That's science, not philosophy.

M: Well, in those days, the term "philosopher" referred to anyone who was interested in discovering knowledge. People who did what we now call astronomy, physics, biology, and the arts, and those who did what a modern day philosopher does — they were all called philosophers.

S: Oh! Okay, so what did your Empi find out?

M: Let me begin with the *question* he was interested in. He was puzzled by something that might be obvious to a tenth-grader like you. Why is it that when we close our eyes, we can't see anything? Suppose you are looking at a table. Why does the table disappear from our vision when we turn our head away? Why is it that when we close our eyes, we can still hear, smell and taste?

S: Mom, even a fifth grader knows that. We see an object when the light from that object falls on our eyes. Your Empi guy was pretty ignorant.

M. Hold on, Rafa. Remember he lived 2500 years ago, and he didn't have the kinds of teachers like you do. Actually, if Empedocles hadn't asked the questions he did, Euclid may not have constructed his theory of light based on his geometry. And if Euclid hadn't constructed his theory of light, who knows, the modern theory of light would not have evolved. And if modern scientists hadn't come up with a theory of light, your teachers wouldn't have known anything about light, and they wouldn't have been able to teach you anything about light. So you see, it took someone like Empedocles to ask an important question that finally led to what you and I know now about light and vision.

S: So was it Empi who discovered that we see an object when the light from it falls on our eyes?

M: No. That idea came a thousand years later. As I was saying, Empi — that'so much easier than Em…pe…do…cles — Empi was puzzled by the systematic connection between his eyes and his experience of seeing. So he came up with an idea. He said:

1. there is a substance called light;
2. this substance streams from our eyes to the objects in the world; and
3. we see an object when that substance from our eyes touches that object.

S. Gee whiz! Your man Empi was quite daft, wasn't he? We see an object when light from that object hits our eye. Light doesn't *stream* from our eyes. What is this? Is light like an eye-saliva or something?

M. Stop, Rafa. Empi wasn't stupid. It just happens that given what we know now, his idea was wrong.

S: Okay, Empi wasn't stupid. But he was wrong. Same difference.

M: Huge difference, actually. Are you stupid?

S: No.

M: But you can be wrong sometimes, right? Actually, quite often.

S: Alright. Empi was a very smart guy whose theory of light was wrong.

M: Now let me ask you, how do you know his theory is incorrect? Your teachers say that we see objects when light from those objects hits our eye. Empi says we see objects when the light streaming from our eyes hit those objects. How would you find out which one you should believe?

S: I don't know… I need time to think.

M: Okay, take your time. We'll talk about it tomorrow after school.

Dialogue 2: Vision and touch

M: Rafa, there is an email from Dad about Empedocles.

S: About Empi? That's weird. We were talking about him yesterday. And Dad sends an email today? Is he clairvoyant? Mom, this is extra-sensory perception.

M: Hah! Your Dad clairvoyant? Not in a million years. I talked to him on the phone last night about our conversation.

S: Where's his email?

M: Here, take a look.

Zin, could you print this and pass it on to Rafa, please?

Dear Rafa,

As your mom told you, Empedocles was not a stupid philosopher. Famous scholars like Euclid, Plato, and Aristotle accepted his theory. It was only a thousand after he proposed it that someone showed that it was wrong. And you know what? A thousand years from now, if there are still humans left in the world, there might be a kid reading about what your teachers have told you, and saying, "Those teachers of Rafa's! How stupid can one get?"

Why did Empedocles suggest the idea of light streaming from the eyes and touching what we see? Consider how you perceive the world through touch. Suppose we blindfold you and take you into a room that you have never been in before. How will you get a mental picture of the room? You will move around, waving your arms, and when your hand (or some part of the body) is in contact with an object, you will infer the existence of that object in the room. Right? Empedocles was extending the principle of touch-and-perceive to the sense of sight as well.

Our senses of sight and touch lie at the core of our knowledge of reality. Suppose you were born without any sight and any sense of touch, do you think you would have any concept of reality existing outside your consciousness? True, you might hear people's voices, and over time, you might begin to understand what they are saying, but for all you know, you might think that these voices come from your own consciousness, instead of from the outside world.

Of these two senses, touch and sight, which one do you think has priority? Think about this. If you have the experience of seeing a vase in front of you, you would conclude that there is a vase in front of you. Suppose you extend your hands forward to pick up the vase, and your hands go right through that vase. You can't touch what looks like the vase. Your eyes say that there is a vase in front of you, but you hands say that that there is no such vase. You are faced with a logical contradiction. It can't be the case that there is a vase in front of you and there is no vase in front of you. So at least one of your inferences must be false. Which one would you choose to abandon? Yes, you will conclude that there is no vase in front of you, and what your sight is telling you is an illusion. What kind of illusion? Probably a hologram, a 3-D illusion. So touch has priority over sight, right?

Given that sight and touch are the primary bases for our sense of the external reality, and that touch has priority over sight, it was quite reasonable of Empedocles to have extended the touch principle to sight as well. You extend your hands to touch something to perceive it with your hands, and you extend the light from your eyes to touch something to perceive it with your eyes.

But we in the twenty first century judge the idea to be wrong. Imagine you are living in Sicily 2500 years ago. Empedocles is your teacher, and he is teaching you his theory of light. Think critically about his theory. How would you convince him that his theory is wrong?

You can't just tell him, "But Mr Empedocles, you are wrong." He would pull his thick spectacles down his nose, stroke his beard, fix his eyes on you, and say in his deep voice, "Okay, tell me, Rafa, why do you think I am wrong?" You can't reply, "Because that is not what my teachers taught me!" You will have to point out the flaws in his theory, based on what Empedocles and you can see on your own. What would you say to him?

Dad

Dialogue 3: An argument against Empedocles

S: Mom, I think I have a good argument.

M: Argument for what?

S: Against Empi's theory of light.

M: One minute, let me send this email.... Where is my tea?... Okay, Rafa, tell me, what is your argument against Empedocles?

S: Dad asked me how I would convince Empi if I were in his class, right? Let's pretend that you are Empi, my teacher, and I am in the classroom. Ready?

M: Yes.

Student: *Mr Empi, Sir, I would like to convince you that we see things in the world because light from them fall on our eyes, not because light from our eyes streams out and touches them.*

Teacher: *But ordinary objects don't emit light, do they? A candle emits light, but the vase over there doesn't emit light. So how come we both can see the vase?*

Student: *Light from the sun or from a lamp gets reflected from the vase. We see the vase because of reflected light.*

Teacher: *Okay, your theory is a possible one, but I don't see why my theory is wrong.*

Student: *I would like you to imagine that you are sitting in a totally dark room. There is a vase on the table in front of you. If the room is completely dark, you can't see it, but if you turn on the light, you can see it. If there is light streaming from your eyes, how come you can't see it?*

Teacher: *Hm! That's a tough question. I may have to say that in addition to light streaming from my eyes, there has to be some other light falling on an object for me to see it.*

Student: *What if there are many others beside you in a dark room staring at the vase on the vase. If your theory is right, wouldn't you expect the light streaming from their eyes to light up the vase so that you will be able to see it even if there is no other light?*

Teacher: *I see what you are leading up to. I will have to say that the light streaming from our eyes is a different kind of light. It does not illuminate objects.*

Student: *Notice that the theory that I am supporting doesn't need two kinds of light. The light from the sun or a lamp that illuminates an object is the same light that falls my eyes so that I see that object. So my theory is actually much simpler than yours,*

Teacher: *I will have to think about it. I am not fully convinced though.*

Student: *Sir, can I show you a small experiment. I want you to look at this table lamp.*

Teacher: *Okay, I am looking at the table lamp.*

Student: *I am going to turn this on. There I have done it.*

Teacher: *I can see that.*

Student: *You see that the brightness of the lamp has increased, right?*

Teacher: *Yes, I do.*

Student: *What caused the brightness to increase? Is it something that I did to the lamp, or something that you did to your eyes?*

Teacher: *Well, I didn't do anything to my eyes. I didn't do anything with my eyes either: I was just looking at the table lamp the same way. So it must be what you did with the table lamp.*

Student: *It is quite reasonable to say that by switching it on, I increased the light coming from the lamp. Would you agree?*

Teacher: *Hm! I don't think I have a choice, do I? I can't think of any other explanation for the lamp appearing to be brighter.*

Student: *The theory of light streaming from our eyes won't explain why you experienced increased brightness when I switched on the lamp. But my theory says that you see an object when the light from that object falls on your eyes. It follows that when there is an increase in the* *amount of light, you will perceive an increase in the brightness of the object. So my theory explains why turning on the lamp causes the perception of increased brightness.*

Teacher: *Right!*

Student: *My theory explains what your theory can explain. In addition, it explains what your theory can't explain. So my theory is better than yours. You are a scientist, Mr Empi, Sir, so when there are two competing theories, you are forced to accept the better one. So you have to reject your theory and accept the theory that says that we see objects because light from the objects fall on your eyes.*

Teacher: *Why can't I accept your theory, but also keep my theory? Why should I reject my theory?*

Student: *Because given my theory, your theory is not necessary. It serves no purpose/*

Teacher: *Okay, I accept your theory. You are bright young boy. I see a bright future for you, brighter than that table lamp.*

Student: *Thank you, Mr Empi, Sir!*

M: That was very good, Rafa. You obviously did your homework. Did you take the idea from Alhazen?

S: Al-who?

M: Alhazen. He was an Islamic scholar who lived in Cairo in the eleventh century. His actual name was Abu Ali Hasan, but he was called Alhazen in the West.

S: Never heard of him. What did Alhazen do?

M: He was the one who showed that Empi's theory was wrong. And he used a similar move. He pointed out that if we have been sitting in the dark, and all of a sudden we turn our eyes towards the sun or another very bright source of light, our eyes hurt. That means something from the bright light source must be hitting our eyes. You have adopted a similar line of thinking, but I like your argument better.

S: Wow! So that means if I were living in the ninth century, I would have become famous for my study of light.

M: Probably. Too late now.

Dialogue 4: Things appearing smaller at a distance

S: Mom, wasn't it the middle eastern guy Alhazen you were telling me about yesterday who worked out the laws of reflection?

M: Yes, it was him.

S: What about the idea that light travels in straight lines? Did Alhazen discover that too?

M: No, that was Euclid, long before Alhazen.

S; The mathematician Euclid that my geometry teacher told me about? How come he did physics?

M: I told you, Rafa, in those days people didn't cut up knowledge into water-tight boxes.

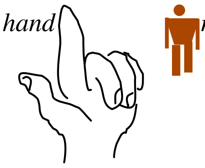
S: Euclid was also Greek, right?

M: Yes, he lived in Greece around the third century BCE. Oh, wait. I almost forgot. There's another email from Dad on something related. I want you to read it before we talk about Euclid. Here.

Dear Zin, could you show this to Rafa, please?

Dear Rafa,

There is something that I would like you to think about. You know that when an object is farther away from us, it appears smaller. When you stand next to me, I am much taller than you, and taller than your mom. But when your mom is near you and I am farther away, I appear smaller *than your mom and even you. If I moved far enough away from you, I would appear as small as your finger:*



Can you come up with a theory to explain this?

After dinner last night, I was thinking about the discussions on light and vision that you and Mom have been having, and wishing I could be there to join all the fun. Then I remembered an interesting incident a friend of mine told me about a three-year old girl.

When my friend visited the girl's parents a few years ago, they decided to go see a giant Buddha statue in the middle of a lake. During the boat ride, the little girl kept looking from the statue to the shore and back again. On the return journey, when the boat got close to the shore, she said, "When we were going, Buddha got bigger and bigger. And when we were coming back Buddha got smaller. Now it is the regular size."

That got me thinking. A grown up would have said that the actual size of the statue remains the same, but it appears smaller when we are away from it. This is only an optical illusion. But the girl interpreted the appearance as reality, and concluded that the statue physically got bigger and then got smaller.

Fascinating, isn't it? By the time children are five or six years old, they understand, without anyone teaching them, that distant objects appearing to be smaller is an illusion. I am not sure how they figure it out, but here is a possible scenario. We can compare what our hands tell us and what our eyes tell us. If we hold a pencil in our hand at close distance and then hold it as far away as the length of our arms permit, we can see that the pencil appears to be smaller as it moves away. But when we touch it, our hands tell us that the size of the pencil is the same. Given the conflict between what the eye tells us and what our hands tell us, we assign greater credence to the hands, like I said in my previous email about the hologram.

Time for me to catch my flight. Talk to you later. Think about the question I asked you: why do things appear smaller when they are farther away?

Dad

S: Mom, why do things appear smaller when they are farther away?

M: Rafa!

S: Yes, Mom!

M: What do you think, am I going to give you a readymade answer?

S: You are going to ask me to come up with my own theory. But Mom, I had a loooong day in school. I came home and did all my homework. I am tired and sleepy…

M: What, you think you can take me on a sympathy trip? Forget it, Rafa, go figure it out on your own. Go.

S: Good night, Mom.

M: Good night, Rafa.

Dialogue 5: A bit of geometry

S: Mom, I think I have a decent theory.

M: Theory of what?

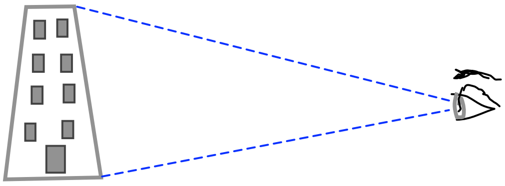
S: A theory that explains why things appear smaller at a distance.

M: I am all ears, Rafa.

S: Let us assume that light travels in straight lines.

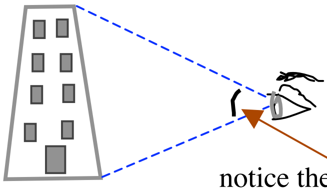
M: We can assume that.

S: Imagine I am looking at a distant building. Light comes to my eyes like this. I need to draw a picture.



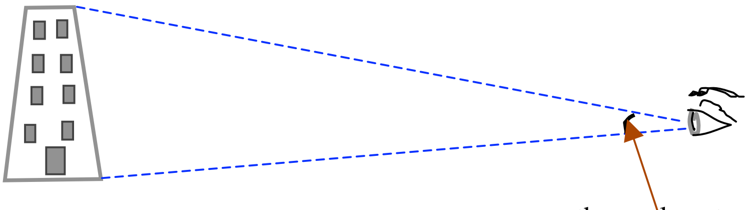
Here is a building. Here is my eye, looking at the building.

The blue dotted lines are light coming from the top and bottom of the building to my eye. Now, if my eye gets closer to the building,



notice the <u>angle</u> of the dotted lines gets bigger,

but if the eye moves away,



the <u>angle</u> gets smaller.

Okay, so that explains it.

M: That explains what?

S: That the building, or some other object, looks smaller when it is farther away.

M: No, that doesn't explain it. Not yet, at least. What you have said is this.

Principle 1: Light travels in straight lines.

From this, given what we know about geometry, it follows that the angle at the eye gets smaller when the eye moves farther away. But that says nothing about seeing something as smaller or bigger.

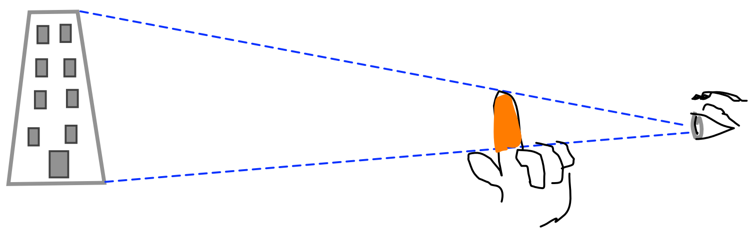
S: Oh, okay, I need two principles, not just one:

Principle 1: Light travels in straight lines.
Principle 2: The perceived size of an object depends upon the angle that it makes on the eye.

Given what we know from geometry, it follows from principle 1 that the angle at the eye gets smaller when the eye moves farther away. Given principle 2, it then follows that as the eye is farther away from the object, its perceived size gets smaller.

M: Very good, Rafa. But can you use these principles to explain why your finger at close range appears as tall as a building?

S: Yes, I can. It is quite straightforward, actually. Look at this diagram:



The angle projected by the building on the eye is equal to the angle projected by the coloured part of finger. Given principle 2, it follows that we would perceive this part of the finger and the building as the same size.

M: Excellent. You know, the argument that you raised against Empedocles a couple of days ago was very close to the one that Alhazen raised against Empedocles. The theory that you have constructed now is what Euclid constructed.

S: Really? Wow! So if I had been born before Euclid I would have been as famous as he was!

M: Not as famous as he was, because Euclid's fame is built on the geometry he constructed. His contribution to the study of light was important, but not as monumental as that of geometry. But you would definitely have been famous.

S: But Mom, Euclid's time was soon after Empi's right, long before Alhazen?

M: Yes.

S: So wasn't he following Empi and assuming that light streams from the eye and touches the objects we see? If he made that move, how could he explain how things appear to be smaller when farther from the eye?

M: For your theory, does it really matter whether light travels from the eye to the object or from the object to the eye? So couldn't Euclid have used the same diagrams that you have?

S: Oh, yes, I see.

M: Alright. One question though.

S: What?

M: Your principle 1. You crucially need that principle for your theory to work. Do you have any independent evidence for that principle?

S: Independent evidence?

M: Meaning, is there some other phenomenon that requires you to assume that light travels in straight lines?

S: Oh! I don't know. Is there?

M: You find out. Not my job. My job is to push you to think, not do your thinking for you.

S: Sadist!

M: When you're in college, Rafa, you'll thank me for being a sadist. Good night, Rafa.

Mathematical modeling vs. calculations

Dear Rafa,

Mom told me about your theory that answers the question raised in my last email. I am proud of you, Rafa. You are thinking like a scientist. If you decide to become a scientist, I am sure you will become an accomplished one.

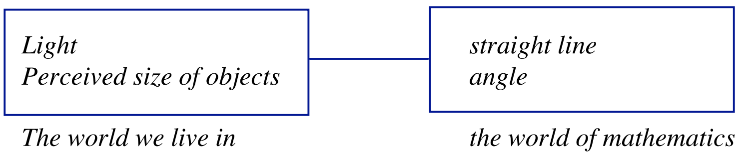
I am not saying that I want you to become a scientist. Whether you want to be scientist, a school teacher, a carpenter, an engineer, a musician, a dancer, a farmer, or something else is for you to decide. You may also decide to be a homemaker — a "house-husband" if you will — like my friend Izen. He decided to stay at home and take care of the kids for ten years so that his wife could pursue her career that meant so much to her. Mom and I are not going to tell you what to do, but we will help you develop your capacity to make your own decisions. For us, all that matters is that you shouldn't have to regret the choices you make, and that they will lead you to a fulfilling and happy life.

Let me go back to your principle of light traveling in a straight line. Implicit in your explanation was that of ***mathematical modeling****. Take the two principles you have postulated:*

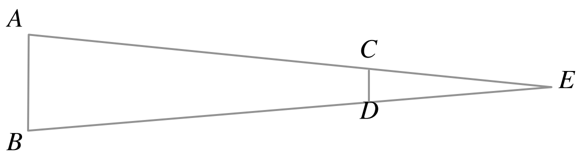
Principle 1: *Light travels in straight lines.*

Principle 2: *The perceived size of an object depends upon the angle that it makes on the eye.*

Of these, light and perceived size of the object are entities in the real world, but straight line and angle are entities that exist in the world of mathematics. The theory that you have constructed abstracts away the properties of the world into objects existing in the world of mathematics. That is mathematical modeling.



Given this move of mathematical modeling, the essentials of the picture that you drew of the building, the eye, and your finger in between, for instance, can be abstracted as the following:



This is a representation of a particular situation in the world that derives from your mathematical model. AB represents the building in your drawing, CD represents the finger, and E is where your eye is. Notice that what you have here are two similar triangles AEB and CED. You can prove, using your knowledge of geometry, that in similar isosceles triangles, the size of a side (AB vs CD) increases with the distance from the opposite angle (E). This is the result you were appealing to in your theory.

Another use of mathematics in science is that of making ***mathematical calculations****. Suppose I were to ask you, "Given a building of 500 meters at a distance of 100 meters, how far from the eye should a finger of 5 cms be placed such that the building and the finger appear to have the same size?" In terms of the above picture, this question translates as: given that AB = 500, CD = 5, and the perpendicular from E to AB is 100, calculate the length of the perpendicular from E to CD. Can you do that?*

Dad