Brilliant-cut diamonds and other tricks of the light

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Today, I am going to talk about something that is mathematically rather simple, but I hope that you will still find parts of it unexpected and interesting, and hopefully you will find something that you can go away and try out when you go home. The mathematics behind it will be geometrical and rather simple - the geometry of the reflection and the refraction of light, and one or two places where you might not have expected those features of light to play an interesting role.

What we are going to look at first are some features of diamonds and their brilliance; why they are brilliant and how they need to be cut in order to be as brilliant as possible. If you are in possession of a diamond ring you might well find that the diamond has been cut in a rather particular and spectacular fashion, which is known as brilliant-cut. What is characteristic about this cut is that it has got a girdle region around the middle, which is a thin annulus around the diamond, so that you do not have a nasty sharp edge which will catch on things or cut things; there is also the top part, which is called the crown; and the bottom area is known generally as the pavilion. The characteristic structure of a brilliant-cut diamond can be seen schematically here:

This type of diamond shape has only been around for about ninety years or so, and the person who was responsible for inventing this shape was Marcel Tolkowsky. He died not that long ago, having lived to a pretty good age. He came from a long dynasty in Belgium, a family greatly involved in diamond cutting and polishing and dealing, over many generations. If you spot a news story on the BBC - every few years, a story will come up about the latest biggest diamond that has been discovered and is being cut - almost certainly, the person who will be cutting that priceless diamond will be Gabby Tolkowsky, the grand-nephew of Marcel. So this family remains a great name in the diamond cutting business.

Because he was a rather able child at school, Tolkowsky was sent to be a student at Imperial College in London in the early years of the Twentieth Century, so he began as a student in about 1918. He was destined to complete a PhD thesis there, and the subject of that thesis was to be something to do with the polishing and grinding of diamonds - it was a thesis in the Engineering School. But, in his spare time, he seemed to become involved in another project to do with optics, and in 1919, in his first year as a student, he completed and published a book that became something of a classic, called 'Diamond Design: A Study of the Reflection and Refraction of Light in a Diamond'.

What he considered formally for the first time is what happens to rays of light when they enter a diamond - when they are reflected and refracted within the diamond and then come back out. One of the key questions of the book was whether there is a way to choose the shape of your diamond so that it appears as brilliant as possible when you look at it. What that means is that you do not want lots of the light that goes in to leak out of the back of the stone. You want it all to be reflected back out, straight into the eye of the beholder.

Before Tolkowsky came along, the tradition of cutting diamonds goes back a very long time. So fir probably a thousand years, people were interested in preserving the basic octagonal structure of the diamond crystal, and faces were just polished and not really cut or shaped. But over the generations one began to see some attempts to shape and cut diamonds to maximise the amount of reflectivity that you would get.

What Tolkowsky said was that what we need to do was to study the optical properties of light entering this structure and then leaving, to try to work out what is the best possible shape that we could cut it in. In order to do this, we need to know about two features of light to engage. The first is very simple: the reflection of light from a flat surface. So, if we have a plain mirror and we shine a ray of light at that surface and it bounces off, by the law of reflection, if you remember that from your school days, if you make a right angle with the mirror, then the angle of incidence, of the ray of light coming in, is equal to the angle of reflection that the light comes out at:

There is another way to characterise what is being done there, which is rather trivial in this example, but rather deeper we will see in a moment in the case of refraction, that the path that is being taken here between A to C and B is the path that minimises the time that the light would take to traverse the distance from A to C to B. So that, if it was doing something rather wavy, and moving on a curve, it would take longer. So this is the shortest possible time of transit between point A, through point C, to point B.

Let us think a little more about refraction. This is more complicated so let us think about it in a situation that does not involve light at all. Suppose that you are a lifeguard on the beach, and someone is out swimming in the sea and they get in trouble and they are waving their arms hoping to be rescued. The question, then, is where you should run to and where should you enter the water, in order to get to the swimmer as quickly as possible?

One intuition some people might have would be to take a route to the swimmer that is a straight line. That is the route of shortest distance to the swimmer. Alternatively, you might want to get into the water as soon as possible, so you might run straight for the water and then swim from there. This would be the path of the shortest possible path across land. Or, if you are a faster runner than you are a swimmer, as pretty much everyone would be, you would want to try and minimise the amount of swimming you have to do, so you might run along the shore until you only have to swim out to the person in danger in a line perpendicular to the beach. This would be the route where you are swimming for the shortest distance possible. I have marked these three different routes on this picture:

In fact, none of these possible routes are actually the least-time route to get to the swimmer. The route that would take the least time is the red one. The exact position of this line, with the angles the lines make either side of the perpendicular dotted line, is determined by the speed at which you can run in air when you are running on the beach, and the speed with which you can swim in water. So you notice that, when you get in the denser medium, where you travel more slowly, your path bends towards this perpendicular dotted line. So the red path here is the least-time path.

And this is exactly what light does when it goes from a medium such as air into one like glass. The light is bent towards the perpendicular line, because it travels at a different speed in air than to the speed it travels in glass. Therefore, the so-called refractive index of a medium is given by the sine of the angle of the light coming in from the perpendicular line (the incident angle), divided by the angle of the light as it enters the new medium (the refracted angle), and this is simply the ratio of the speed of light in this medium divided by the speed of light in this medium.

That is all the refractive index is: the denser the medium that you are going into - it might be water, it might be glass, it might be diamond - the slower the light is travelling in that medium, and so the more it gets bent in order to achieve the least-time path. So this refractive index is a measure of the change in speed of light going from one medium to another.

Refractive Index = n

= $\sin(\theta 1)/\sin(\theta 2)$

= (speed in medium 1)/(speed in medium 2)

This has some unusual consequences. For instance, it would be possible, if you moved the incident line coming in so that you had a greater and greater incident angle between the light and the perpendicular line, you would find a situation where the incident light is coming in flatter and flatter and eventually is horizontal.

You might imagine you are a fish sitting at the bottom of a pond, and you are looking up at fishermen in the air above or kingfishers that are poised to strike, then light coming in here gets bent towards the normal and comes down to your eye.

You can see from the picture that once the light comes in at an angle which is greater than 'c, it does not reach your eye at all. So the fish, when he looks up at an angle greater than this, sees complete reflection back inside the water, so the fish can only see what is going on in the circle of area above it. If it looks beyond this, things are reflected back from the bottom of the pond.

The angle at which there is no refraction, which is where the incident angle between the incoming ray of light and the perpendicular line - the 'normal' - is 90 degrees, is called the critical angle. The critical angle is just the angle whose sine is equal to 1 divided by the refractive index of the medium which you are looking in:

Critical angle for air-water interface is sin-1(1.00/1.33) = 48.8 deg

For water and air, this angle is going to be nearly 49 degrees. So if you try to look at water at less than 49 degrees, then you are going to see a reflection rather than a refraction.

If we now think about these things in the context of our diamond, you can see that this refractive quality is important if we are to have the light return back as much as possible. Diamond is an extreme material. Of all naturally occurring materials, it has the largest refractive index, so it has the slowest speed for the propagation of light within it. So its refractive index is really enormous: it is 2.42. This means that the light travels 2.42 times slower in diamond than it does in air. I have already mentioned that the critical angle for light to hit water and be reflected is 48.8. For glass, it is about 42, but for diamond, it is 24.4, which should show you how unusual the refractive index is. So if you just try to make a diamond-shaped piece of glass, it will not behave optically in the same way at all.

n(diamond) = sin(i)/sin(r)

= (speed in vacuum)/(speed in diamond)

n(diamond) = sin(iair)/sin(rdiamond)

= 2.42

The importance of this critical angle is that if you shine light inside, and the incident angle is greater than 24.4 degrees, then the light will not be refracted back out but will be reflected back in. If you were in water, you would have to go more than 48 degrees for that to happen, but in diamond, it is only 24.4. So we have got a number of unusual features of diamond, with regard to reflection and refraction, because of this extreme refractive index. In terms of numbers, normal light travels at 186,282 miles per second, but in diamond, it goes at only about 77,056 miles per second.

For light entering the diamond, if it is outside this critical angle of 24 degrees, it is going to be internally reflected off the back face. If you sent it in closer to the normal so the incident angle would be less, when it reached the back face, some of it would be refracted through. This is something you want to avoid when cutting your diamond, because it would mean that it would be less brilliant. So, some of the old cut-diamonds, if you look at them, they have dark spots near the centre. What is happening there is that light is entering near the centre and is being lost. It is being refracted through the back of the diamond and is not being reflected back to you, so the centre looks dull and it does not sparkle. This is why you want to exploit diamond's very small critical angle so as to make sure that the light reflects internally and does not just get lost outside the back.

This is the first feature that Tolkowsky thinks about and is going to have to try and exploit when he comes to pick the exact shape that he is going to have for his brilliant-cut diamond. The second feature that Tolkowsky worried about was something that physicists call dispersion, and which gemmologists call fire.

If you look at a brilliant-cut diamond or a diamond cut in some other form, and you move it around in front of your eyes, what you will see is an appearance of different colours of the spectrum which are constantly changing. One of the dramatic features of high-quality diamonds is this fire, or dispersion, this change of colour.

What is dispersion? Well, dispersion is simply a measure of the spectral decomposition of white light. As Newton first convinced us, white light is in fact made of a whole spectrum of colours of light, with different wave lengths which define their colours, and those different colours move at different speeds. That is why, when you look at the light being split through the prism, the different colours are bent by different amounts, so they have to take a different path in order to minimise their time of getting from one place to another.

Diamonds have, again, one of the largest dispersions of any material. It is not the largest - there are a few unusual minerals that have a larger dispersion. So, the dispersion will be the difference in refraction, the difference in speed, between one end of the spectrum, say the red end, and the other, the violet end. This means that the colours split very dramatically within the diamond and undergo rather different reflection histories, so that, when you look at the diamond and see the light coming back out, the colours are split across the spectrum and you see them behaving rather differently after they have sort of been on their trip around the inside of the diamond. So, one of the tricks to cutting a diamond in an optimal way is to try to maximise this dispersive effect.

What Tolkowsky did was to consider the shape of the diamond, where he had got various things that he could play with. He could change the angles at various points, such as at the bottom of the diamond, around the middle or at the crown on the top. So, he could change the shape of the diamond in changing the angles it was cut at, trying to see which would maximise the dispersion. Of course, you would have to think in three dimensions, where you would need to split up the faces and facets, but it is easily to show it in a two-dimensional picture:

If you make the angle at the bottom too small, you get a diamond like to one on the left-hand side. Here the rays enter from the top and they go through to hit the bottom face at an angle greater than 24 degrees. This means that they will not be refracted, but instead they get reflected to hit the other face at the bottom. However, here they inevitably hit this face at an angle that is much less than the critical angle of 24 degrees, and so they all get refracted and lost. So, in this case, you can meet the condition to have reflection at the first contact with the side once inside the diamond, but not on the next side, because you have made the diamond too deep.

On the right-hand side is the opposite extreme, you make it very shallow at the bottom, then a ray that comes in at the top can be reflected alright at first, because it is less than the critical angle. Then, the next time it comes to the side of the diamond, it again comes at a very shallow angle, bigger than 24 degrees, so it gets reflected there as well, but then, when it comes up to the top again, it gets reflected back and then lost through the lower side of the diamond. So, this is a bad deal because we are aiming to have the light sent back out the top of the diamond again. You would not see very much light emerging from either of these two types of diamonds across many parts of its face.

So what Tolkowsky was able to then was to home in on a design which is not too deep and not too shallow, just in between, in which light rays come in, they have an angle which is bigger than the critical angle of 24 degrees at the first contact with the edge of the diamond, so they get reflected, then are reflected again up towards the top of the diamond again, and come straight back out. This is shown by the diamond in the centre of the above diagram. So, essentially, all the rays that go in and, after internal reflections, come straight back out, and nothing gets lost at the back by refraction. So, this is the special structure, the special shape, that Tolkowsky calculated and proposed should be used.

If you do these calculations, which you can just using the sort of optics you used to do at school, you have a little bit of leeway. This is what Tolkowsky wanted so that you have a little range of angles for which this will work. He also wanted to maximise the dispersion effects, so he had to have a choice. So sometimes, good dispersion would lead to a little less brilliance, so he decided to optimise the product of the two. So to maximise that, there is a little bit of trade-off, but it gives you the best combination of dispersion effects and brilliance. The structure for Tolkowsky's proposed diamond is as follows:

If we call the total width of the girdle of the diamond 100%, then the top will be about 53% and the height will be 59.3%. So, if the total width is 100, these figures would be 53 and 59.3, which would be split into 16.2 at the top and 43.1 at the bottom. So these were the proportions that he originally focused on as being optimal from these two points of view: to produce this fire effect; and also the maximum back-scattered brilliance.

Because it is nice to see what Tolkowsky said on this, his original words from his book of 1919 are as follows, which make sense through the picture that follows:

'For absolute total reflection to occur at the first facet, the inclined facets must make an angle of not less that 48°52' with the horizontal.'

'For absolute total reflection at the second facet, the inclined facets must make an angle of not more than 43°43' with the horizontal.'

'For[outgoing]refraction, a may be less or more than 45°. When more, the best value is 49°15', but it is unsatisfactory. When less, the best value is 40°45', and is very satisfactory, as the light can be arranged to leave with the best possible dispersion.'

'Upon consideration of the above results, we conclude that the correct value for a is 40°45', and gives the most vivid fire and the greatest brilliancy, and that although a greater angle would give better reflection, this would not compensate for the loss due to the corresponding reduction in dispersion. In all future work upon the modern brilliant we will therefore take a = 40°45'. '

This is a nice example of how very simple geometry and mathematics that was known by high school students in 1919 was used by Tolkowsky to produce this very detailed analysis of this simple problem. His Diamond Design book is very rare. If you see a copy in a second-hand book shop - it is about 100 pages long - buy it and give it to me for Christmas! But if you look on the web, there is a complete electronic version of it available for free, to read on the web. It is well worth looking at.

Nowadays, people do things rather more dramatically and in a more high-tech fashion. In Moscow, there is a Russian group who specialise, at the Gemmology Institute there at the University, in analysing all aspects of diamond structure and reflectivity and so forth. They have some wonderful video clips of a sequence of simulations to show the effect of changing the angles of the diamond and its effect on the brilliant and dispersion.

I want to go and talk about something very different now. It is still about reflection, but it is about mirrors. Mirrors are rather familiar, so familiar in fact that we tend to ignore some of their remarkable properties, and I want to spend the rest of the time talking about some of the properties of mirrors and reflection.

Looking at a mirror immediately reveals the most impressive feature. You might be holding a book in your right hand, but when you look at your reflection in the mirror, your reflection is holding the book in its left hand. You might be scratching your head with your left hand, but in the mirror, your reflection will be scratching its head with its right hand. So, whenever you look at yourself in the mirror, you are swapped over, as it were, from right to left.

This might be rather more impressive to think about when you consider that although things are reflected from right to left, they are not transposed up and down. It might strike you as strange that this is the case when you first think of it.

So what is going on here? Well, if you think carefully about what is involved, looking at the mirror, there is a rotation involved, that what you are seeing is equivalent to you turning around almost and going behind the mirror.

A nice example is to take perhaps a piece of paper, which has got something written on it, you hold it up in front of the mirror. You will then see the writing as back-to-front, flipped from left-to-right. But if you have an overhead-projector transparency, or some other see-through clear piece of material which you can write on, and you hold that as you would normally read it in front of the mirror, then you will see the words the correct way around in the mirror. Whereas, when you are holding the paper up to the mirror, you have carried out a rotation, so you are not looking at what you would normally see, so that is why the image on the mirror is also rotated. You would need to step around, as it were, behind the mirror and look back in order to see the image that you are showing the mirror. So there is no such transformation in the up-down direction, just in that right-left sense.

This is an image I tried to get with my transparency in the mirror. Unfortunately, I am not a terribly good photographer, particularly with my mobile phone, but you should be able to see that I have written 'Mirror mirror on the wall' on the transparency which I an holding in my hand, but beyond that is my reflection, with the writing showing up the correct way around for us to read it.

If you start to look at more interesting types of mirror, the situation deepens a little. So suppose, in your bathroom you have some angled mirrors that you can move at different angles, a typical sort of bedroom-type dressing table mirror. So it is hinged, and if you wish, you can have the two mirrors flat, in effect, as a single flat mirror, or you can change the angle. If you have them flat against the back, so you have a single flat mirror, and you look at it, you will see your wedding ring on your right hand, because you are actually wearing it on your left hand, just as normal. But now suppose that you change the angle of the mirrors, so you bring out the sides of the mirror towards you, what happens then?

Things remain the same - your wedding ring is still on your right hand in the image - until the angle to the normal reaches 45 degrees, so the two mirror will be at 90 degrees to one another. At that stage, things change around. Your wedding ring is back on your left hand in the mirror, just like it is in real life.

Why is that? If the mirror was flat against the back, a ray coming in just goes straight back out. But if we move this mirror to an angle, the ray coming in gets reflected around, and it does not go straight back out along the same type of path. We can continue doing this until we reach 45 degrees, when the ray coming in to hit on mirror will be reflected across to the other mirror, where it will be reflected back to us. So the rays are reflected twice, off the two mirrors, at 45 degrees each time, making it come straight back out at 90 degrees, as it would be if the mirror were entirely flat, which means that there is no handedness reversal.

It we keep going and we make this angle bigger than 45 degrees, make the mirrors get closer and closer and closer together, something new happens when the angle between the two mirrors is reduced to 60 degrees. Here your ring is back on your right hand, because it switches back.

This happens because 60 degrees makes it something of a funny angle. This is because if a ray was to come in, it would reflects off the first mirror at 30 degrees. But it then hits the second mirror at an angle of 90 degrees, which means that it just comes straight back to the first mirror again and then back out along exactly the same path. So this strange configuration produces exactly the same situation as though this ray was coming in, hitting the flat mirror and going back out. So, for all practical purposes, when you look at this configuration, you see as though you are looking at a flat mirror and your wedding ring is back on your right hand.

Well, mirrors are odd things. We're used to how our faces appear to us in the mirror, but none of actually know what we look like. We have only seen our faces in mirrors, and our faces are slightly unusual because everyone's face, pretty much, has some asymmetry, so the first odd thing is that this right/left reversal of your face really does make you look a bit different. But the main thing I want to ask now about your image in a mirror is: what size is it? So, as I say, we are used to this right-hand/left-hand bias about our image, but we have also got a rather odd bias in how large we think our faces are. This is an interesting question for people who make mirrors because you will want to know how big you need to make your mirror to be able to fit people's faces in it. So what size should you make a mirror in which you are going to see your face? You might think that it depends how far away people are going to use it. But there is something odd about mirrors: however far away I hold it, my face exactly fits into the mirror. So if I put it over on the wall away from me, my face will exactly fit in the mirror.

There is something slightly odd going on here, and, again, if we draw a few light rays, we can see what is going on.

What we are looking at here is light is coming in, it is bouncing off a mirror, and it is going into your eye, and we need to see the rays coming down from the top of our head and those coming up from our chin if we are going to be able to see the whole of our heads. What is curious about this effect is that the size of the image - what you see in the mirror - is always half the size of your head.

You can go home and prove this for yourself: wait till the bathroom has got very steamy, after you have got out of the shower, when the mirror is covered in condensation, and look at yourself at the steamy mirror, and just draw a little circle around the image of yourself in the mirror. But then step back and have a look at it, and you will find it is really quite small, it is half the size of your real head.

And so, this mirror, and the size of any hand-held mirror, does not need to be any bigger than half the size of an average human head, and it must not be any smaller. Moreover, it does not matter how far away from me you hold this; however far away you look at my image in it, it will always be half the size of my head.

We can see why this is the case if we imagine dividing up our face into four parts. Both of the upper two of these we will call a, and both of the lower two we will call b. If we imagine that our eyes are at the point between the a's at the top and the b's on the bottom meet, I believe that the eyes will be roughly in the middle. However, although the two a's will be the same size and the two b's will be the same size, the a's and the b's do not need to be the same size. So, the total height of my face will be 2a + 2b. We can now put this into the same diagram as before.

The light ray that is coming in from the top of my head, hits the mirror and comes back to the point of my eyes in my face. The angle of the ray hitting the mirror will be the same as the angle of it leaving the mirror, which means that the length of the line of the ray going from the top of my head to the flat mirror will be the same as the length of the line coming back from the mirror to my eye. It is all symmetrical. This is also the case for the ray of light coming from my chin. This means that, although my face is always 2a + 2b, the size of the reflection of my face is only a + b. This is explained by the fact that whatever the distance of the viewer, light from the top of the head is reflected from the mirror at a point half-way between the top or bottom of the head and the eyes.

It does not matter how far away I am: exactly the same argument applies. These angles change - as you move away they become smaller - but the distances between the top of my head and the bottom is always still twice the distance between the top of my reflection's head and its chin. So, if you are making a mirror on the wall somewhere, in the restrooms where people are going to look, you do not need to make it any bigger than half the size of the average human face. But if you do not believe me, just go and try it when you get home!

The last collection of things I want to talk about quickly are really about making things disappear. There is an interesting collection of examples in mathematics that ask: can you make objects which, in some sense, in principle, are invisible? The answer is that you can, so long as you define what you mean by 'invisible'.

In quantum optics, there is a real way to make them invisible, but I am not going to talk about that today. All I mean here is that, if you have an object which, when you look towards it, you cannot see it. For instance, it might be that when a light ray comes in, it gets scattered around within the object in some way, so that when the light ray finally leaves, it is going on exactly the same path that it would have gone on if the object were not there. In this way, in some sense the object is invisible, because it does not have any effect, in perfect conditions, on that light ray. Of course, in practice, the light loses a bit of energy by absorption and some scattering, but you can see the idea in the unusual shape of the following image, which undergoes a sequence of scattering that then leaves the light path exactly the same as what it was before.

There are rather more elaborate examples of this type of thing, where simple laws of reflection that we have been looking at result in an outgoing ray that is the same as the incoming one. But in whatever form you have it, you always need at least four internal reflections to create an invisible object of this sort.

The real experts on invisible objects do not spend a lot of time in physics laboratories, because they are the professional magicians. There are a couple of famous examples, now well-understood, so I do not think I am running the risk of upsetting anyone in the Magic Circle. The first I will consider comes from the Nineteenth Century, which was the great age of public magic, particularly in London. There were great venues, theatrical venues, where great magicians of the period would perform tricks to huge audiences, and there was a huge research activity, in effect, in thinking up new ideas, new tricks, based upon physics and optics, to impress people.

One of the most inventive people was Henry Dircks, and one of the great organisers of this type of research and activity was someone called Pepper, who was appointed as a researcher at the London Polytechnic Institute, which was in Langham Place, just off Regent Street. This was a bit like Gresham College in many ways: it had public lectures, it gave courses in many areas of science, it had standing exhibitions and laboratories and so forth, but it was much wedded into parts of the entertainment business as well, using science for entertainment purposes as well as for other purposes.

One of Dircks' great inventions was something that became known as Pepper's Ghost, which is best understood by looking at pictures:

The audience are in a darkened auditorium, looking at the stage. Unbeknownst to the audience, there is a sheet of glass coming up across the front of the stage. People would not be able to see this. You would think that you were seeing people like me moving around on the stage, and to some extent, you were, but you could create an illusion by having a brightly lit object down below the stage, whose image is refrected through this image. The audience are seeing what is down below the stage. So, if you do this skilfully, the audience will think the ghost is on the stage, that it is moving around and interacting with other actors, whereas in fact you are just seeing the reflected image of something which is off-stage. This is a very simple trick, but it requires highly polished mirrors and very careful stage-craft, so it is not at all easy to do.

The second and last of these extraordinary little tricks, which we still sometimes see on television variety shows today, is known as Proteus Cabinet. Proteus was a Greek sea-god who could turn into any form he wanted. This was invented by Thomas Tobin, who was a very young man, about twenty years old, and he had been attending some of Pepper's talks and demonstrations at the London Polytechnic around 1860. The Polytechnic opened about 1838, so it had been around for a long time by the time Tobin attended. By careful study of optics, he came up with an idea, which, unfortunately, in a way, was performed first by Pepper in the lecture rooms at the Polytechnic Institute. It was as though I had invented this and demonstrated it in this lecture hall to you here on this stage, which is not really the way to do it. You really needed it to be performed in the right type of theatre, by a professional performer, in a very grandiose and spectacular way.

Well, what was the idea? The slogan of the act, the cabinet, was 'Here, but not here.' Here is diagram of a typical cabinet.

It has got four wheels, so you can see underneath, and when you open the front door and look in, you see a central pillar in the middle, and usually there's a lamp put on the top, so it's made to look a bit like a gas lamp. So, you look into a box, you see the side walls, you see the back, and you see this lamp. And then somebody steps into this box, and the door is closed. Shortly afterwards, the door is opened and the person has disappeared, and sometimes the box might be sort of spun around slowly while the person is disappearing so you can check they are not stepping out of the back.

In America I think, Houdini did a version of this trick with extra ingredients, in which an elephant disappeared. The one clue: apparently the man selling programmes remarked to the press that nobody knew where the elephant had gone, but he said he did notice that when the box was brought onto the stage, it only took two people to push it on, but when everyone had gone and it was taken off, it took nearly thirty people to push it off - so he had a very good idea where the elephant went!

So, what goes on here? I think this was the first sort of magic cabinet trick, and the first trick where everything, in effect, was done with mirrors. So that was the remarkable contribution of young Thomas Tobin; he was the first person to realise that, by clever use of mirrors, you could make people see things which were not really there.

What is going on in this trick can be more easily explained by the following diagram:

When the box is first open, there are two mirrors at the back, which are flat, they are moved flat against the walls, so when you look in, you just see the square box with the pillar in the middle and the lamp. But when the door closes, what is being done is that the mirrors are moved away from the walls pm the sides, so that they form a V in the centre. Again, all the joints have to be rather perfect, the angles exactly 45 degrees, everywhere. In the space that is then created behind the mirrors that connect to the pole in the middle, a person can be hidden behind there, so the person who goes in goes into this zone behind, moves these two mirrors in place, and is then enclosed by the two 45 degree mirrors. But ,as we have seen earlier, if you look in, what you see, because of the way the reflections work, is as though there is completely flat back to the mirror, just as before.

There is also a remarkable zone at the front, in the front-most portion of the box. When you look into the box, you see reflections, light ray comes in, hits the side, comes straight back out, but, in the large versions, the impresario can step into this safe zone at the front and they can wave their arms in this zone, so long as he stays within it, put something in and say 'Look, there's nobody there,' etc. Nothing you do in that zone will show up by reflection anywhere else in the box. So it is mighty clever, and it works very well in surprising people and making them think that it must be magic.

So, very simple optics enables you to do something which, even today still, if you see it performed with great panache and style, is very impressive, and there is a lot more to it than just obviously knowing these angles and the structure of the box. To actually get this to work, to get the angles correct, to make it into a show, requires a good deal more than simple physical optics.

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