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Illumin Article

Snapping Spaghetti: The Mystery of the Pasta Strand and Flexural Waves

Abstract

If a strand of spaghetti is bent and snapped from its two ends, the strand will not break into two pieces as do most objects do, but will usually will fracture into three or more pieces. This phenomenon peaked the interest of physicist Richard Feynman, who was not able to explain why the spaghetti breaks in such a way. In 2005 two physicists, Basile Audoly and Sébastien Neukirch, conducted a study and applied Kirchhoff's elastic equations to the spaghetti and successfully modeled the behavior; they also described the mechanism responsible for this phenomenon to be flexural waves causing cascading fractures in the spaghetti strand. In 2014, Destin Sandlin, an educational youtube creator, filmed the snapping of the spaghetti at one quarter of a million frames per second, revealing the flexural wave and cascading fracture process at an unprecedented resolution. These studies revealed the fascinating complexity and beauty of everyday phenomenons otherwise taken for granted.

Introduction

Spaghetti, and pasta in general, is a staple food for many households. Simply boil water, throw spaghetti in for twelve minutes, pop open a jar of pasta sauce, and there you have it: a delicious meal is served. While cooking your meal, you may end up carelessly breaking a stick of spaghetti. Most will simply pick up the broken pieces and throw them away while mumbling to themselves about what a waste it is. However, before you do so, take a closer look. You will notice that the spaghetti is not quite behaving as you would expect it to. Our humble spaghetti stick holds a very elusive secret.

If you haven't already, go to the kitchen and get a stick of spaghetti. Hold the stick on both ends and bend the stick upwards until it breaks. You will find that instead of the spaghetti breaking into two pieces like just about everything else does, it will almost always break into three or more pieces. This behavior is the mystery of the snapping spaghetti. As odd as it may sound, this simple kitchen accident has confused physicists for a long time. It was not until very recently that the physics community uncovered the truth behind this fascinating piece of pasta.

History of Spaghetti

Before diving into the research right away, we first need to understand the origins of our noodle friend. Contrary to what you may believe, pasta did not originate from Italy. Noodles were actually born in ancient China. In 1292, after a 17-year long service in the courts of Kublai Khan, Marco Polo returned to

Source: history.com

We give thanks to Marco Polo for pasta

Venice from China and brought along with him many items; among these were noodles (Discovery, 2001). The Europeans soon took interest in these strands of endlessly delicious possibilities. Rather than using rice flour to make noodles like the Chinese did, they mixed semolina, a much more readily available ingredient in Europe, with water to produce their own version of the noodles, thus inventing the very first pasta prototype. Over the centuries, Europeans, especially the Italians, have refined the process of mixing water with semolina, resulting in what we have today: the dry, elastic, and brittle spaghetti (Discovery, 2001). Little did the Italians know that this simple mixture of water with semolina would one day puzzle physicists for years.

The Mystery

Physicists have understood why objects snap and break for a very long time. An object placed under a load experiences tension. As the load increases, the load will pull the object with larger force, increasing the amount of tension experienced by the object. When this tension exceeds the maximum tensile stress(see *figure 1*), the maximum amount of load it can hold, the object will break or fracture at single point, snapping in half (Roylance, 2008).

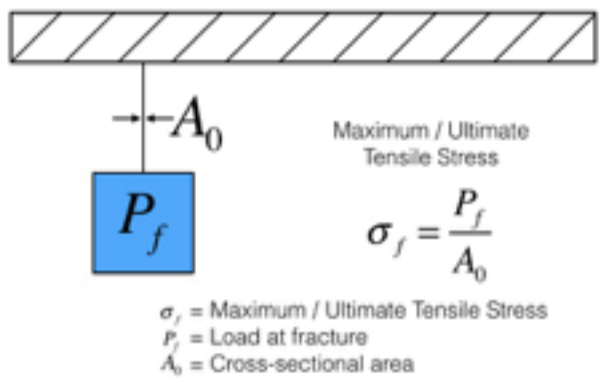

Figure 1: Maximum tensile stress in a linear system

Snapping a spaghetti strand is only slightly more complicated. Instead of a pulling motion, you bend the object. In this case, when an object is bent (*see figure 2*), the bottom of the arc experiences compression, while the top undergoes tension (Sandlin, 2014). The difference in these two forces will compound into a form of bending stress, also known as torque. When the torque exceeds the maximum tensile stress of the object, a fracture occurs in one plane, splitting the object in two (see *figure 2*). The compounding of tension and compression is also why it is much easier to break an object by bending it instead of pulling it apart.

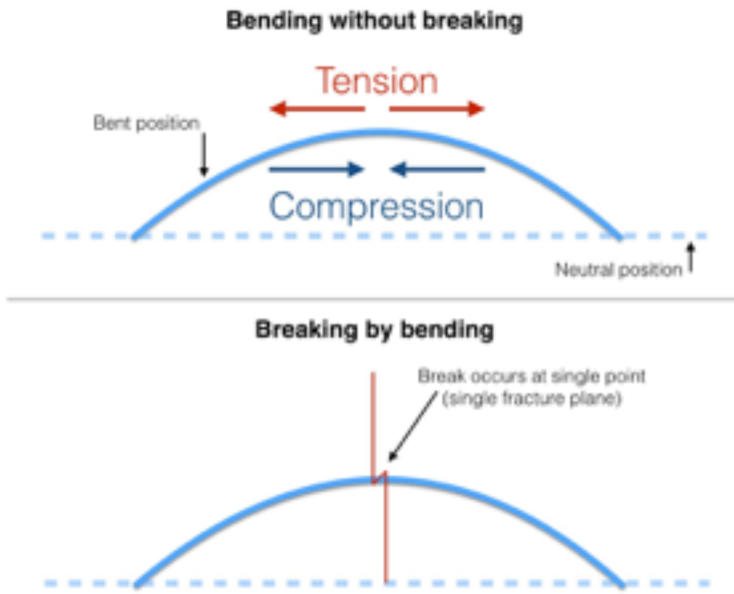

Figure 2: Simple bending and breaking of an elastic linear object

At this point you may realize the confusion that arises with spaghetti. When you bend a strand of spaghetti over its maximum tensile stress, instead of having one fracture, the noodle will fracture in multiple planes, meaning that the break results in more than two pieces (*see figure 3*). This phenomenon did not seem to make sense for physicists and confused them for a long time.

Now let us begin our journey to uncover the secret of our sly friend.

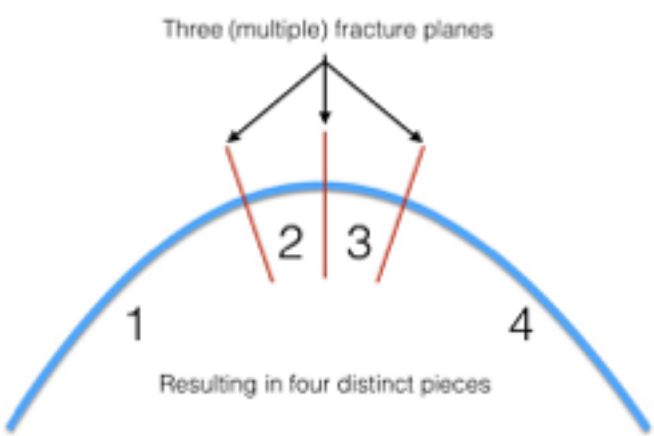

Figure 3: Common fracture scenario for a piece of spaghetti: multiple fractures into multiple pieces

Feynman and Other Explanation Attempts

Our humble spaghetti caught the attention of Richard Feynman, the genius bongo-playing physicist who worked on the Manhattan Project who also received the Nobel prize for his contributions to the field of theoretical physics, namely his Feynman diagrams. While cooking spaghetti with his friend Christopher Skyes, they noticed this strange behavior and ended up spending two hours snapping spaghetti and testing various theories in an attempt to explain this mystery (Feynman, 1994).

If you have been following along so far, you may have felt the two ends of the spaghetti strand at your fingers vibrating after breaking. Feynman thought this vibration was significant enough to cause additional fractures in the body of the spaghetti. As a result, Feynman and Skyes decided to snap some spaghetti in water to try and dampen the vibrations, only to find that the spaghetti was still fracturing in multiple planes (Feynman, 1994). In the end Feynman and Skyes were left with a table full of broken spaghetti but no strong conclusion as to why the spaghetti breaks into multiple pieces. Feynman's failed attempt to explain this phenomenon led to the notorious reputation of our humble spaghetti - even the charismatic physics genius could not explain something so seemingly trivial.

Other physicists subsequently attempted to solve this mystery. Dick Nickalls ran a few simple experiments in his own kitchen to look into the mechanics of snapping spaghetti. He observed that the third piece always ejects outwards from the convex side (*see figure 4*). From this he drew the

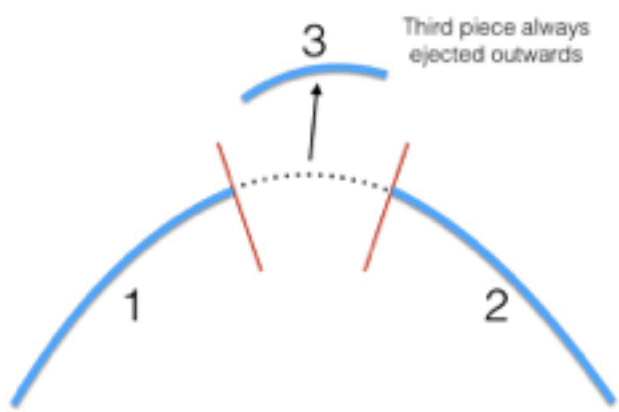

Figure 4: Illustration of Nickalls' observation on outward ejection

conclusion that right after the first fracture, the two remaining pieces spring outward to straighten out due to the elasticity of the spaghetti strand, and this straightening motion causes the third piece to eject outwards (Nickalls, 1995). If this theory is correct, it would mean that if a fourth piece breaks from the same spaghetti strand, it should then be ejected in the opposite direction when the remaining pieces straighten out from the other direction. However, all pieces of the spaghetti, regardless of how many, all eject away in the same direction. Something was still lacking in Nickalls' theory.

Nickalls later also took note there were almost never any additional fractures if the spaghetti snapped cleanly in the middle (Nickalls, 2006). Nickalls concluded that multiple fractures must then have had something to do with the uneven lengths of spaghetti after the initial fracture, and further postulated that the phenomenon had to do with the straightening of the longer piece.

While these theories continued to improve the explanation the mystery, the sly spaghetti continued to keep its lips sealed and remained unwilling to reveal anything. Only recently did physicists rigorously ran experiments to study this behavior and more precisely model the mechanics of the breaking spaghetti strand.

The Study

In 2005, two French physicists named Basile Audoly and Sébastien Neukirch decided to study this phenomenon up close. In a fascinating manner, Audibly and Neukirch sacrificed spaghetti in controlled environments and collected data using a 1000-frame-per-second camera. Audoly and Neukirch found that if one end of the spaghetti was released from a high tension position instead of being bent until broken, the straightening of the spaghetti back into its original shape would result in the same unusual behavior, therefore confirming Nickalls' later assumptions regarding the straightening of the uneven lengths of spaghetti. This discovery meant that the cause of the multiple factoring of the spaghetti was not due to vibrations as Feynman had thought, but rather the spaghetti's attempt to spring back into shape. They called this straightening movement down the noodle a 'flexural wave' (see *figure 5*), a crucial element in solving the mystery of the spaghetti.

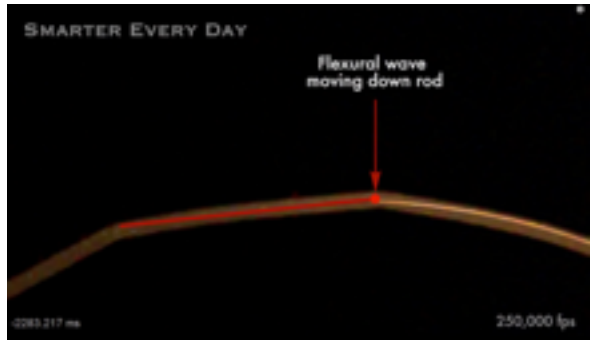

Figure 5: High speed video of flexural wave

After analyzing the data, Audoly and Neukirch found the mechanics of our noodle friend could best be modeled by Kirchhoff's elastic rod equations, a widely used set of equations to model uniform symmetric elastic rods. By using Kirchhoff's equation, Audoly and Neukirch were able to predict the times at which the multiple fractures would occur and model these fractures, called cascading fractures, to a precision that had never been seen before (Audoly and Neukirch, 2005). Audoly and Neukirch were the first physicists to formally study this behavior and comprehensively explain the mystery; through using the already existing Kirchhoff's equations to model the spaghetti, they demonstrated that the spaghetti strands are not as much as an enigma as we thought they were. For the achievement of revealing the secret of our pasta friend, Audoly and Neukirch received the Ig Nobel Prize in 2006, the parody Nobel Prize for trivial achievements (Matt, 2008).

Physicists Still Unsatisfied

At this point you might think that since the mystery had been solved, everyone was happy and content, but this was certainly not the case. Scientists didn't stop there. Being the curious bunch that they are, physicists continued and looked deeper into our poor unyielding spaghetti.

In December 2014, Destin Sandlin, an aerospace and mechanical engineer in Alabama, wanted to explain this phenomenon to the general public. On his Youtube channel, he filmed the snapping of spaghetti at 18000, 40000, and 250000 frames per second with a high speed camera (see *figure 6*). Prior to his video, the fastest video recording of spaghetti snapping had only been at 4000 frames per second. This means that Sandlin was able to analyze the spaghetti at more than 60 times the detail than anyone had done before.

At such a high frame rate, Sandlin observed each fracture happen within a baffling ten micro-seconds of each other. From his video footage filmed at 250000 frames per second, you are able to see the exact moment of the first fracture, the straightening of the two broken pieces, the flexural wave, and the exact moment of the second and subsequent fractures. The footage is so amazing it will definitely send flexural waves down your spine (without your spine breaking, I promise).

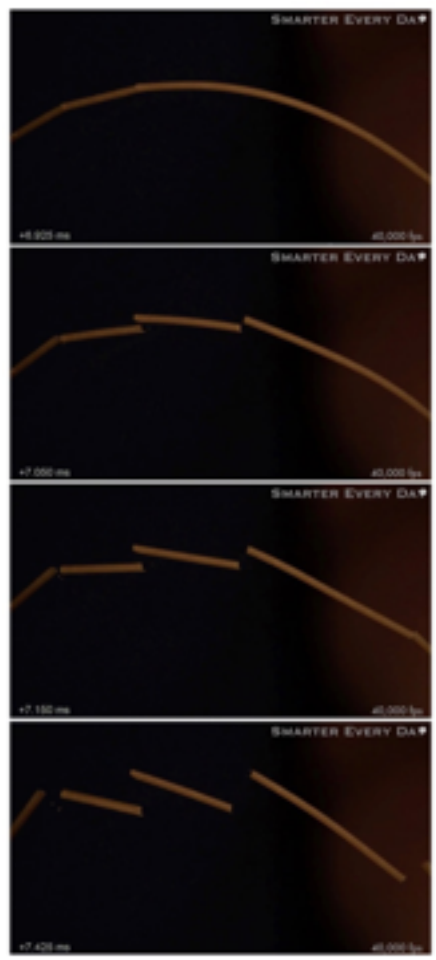

Figure 6: Cascading fracture at 40,000 fps

The Mystery Solved

At this point, after all the research that has been done on our pasta friend, the science community has been able to provide a satisfying explanation of the mystery of the snapping spaghetti.

When a strand of spaghetti is bent, one side of the spaghetti will be under tension while the opposite side will be under compression. These two forces can be combined together as a single force: torque. At the exact moment of the fracture, the two ends near the fracture become free from torque. However there is still a counter-torque built up due to the spaghetti's bent shape. To get rid of the counter-torque, the rod begins to straighten itself out (Sandlin, 2014).

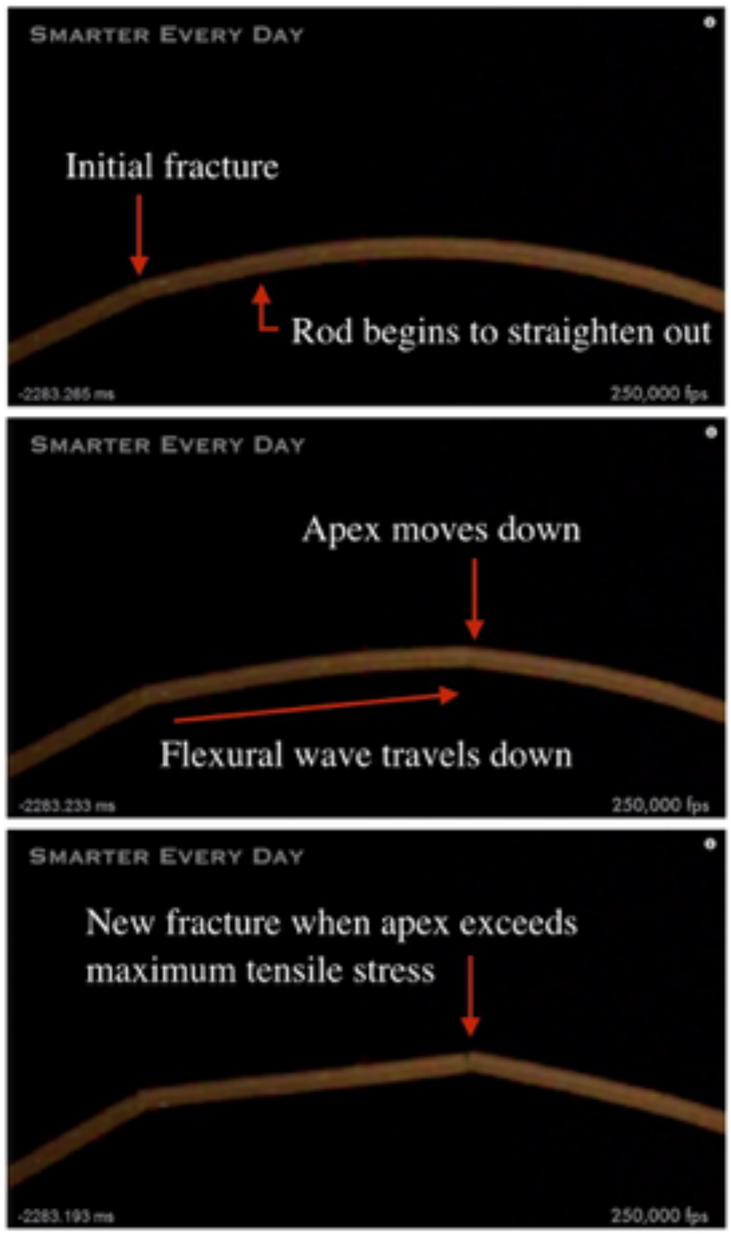

Figure 7: Spaghetti snapping at 250,000 fps

Let us now consider the longer of the two remaining sections of the spaghetti (see *figure 7*). The end near the fracture is straightening out, while the other end of the spaghetti is still bent. The point where the straight section meets with the bent section, or the apex, will have a sharper bend than before. As more of the straight section extends out, the apex will move towards the far end of the strand. This movement of the apex is the flexural wave Audoly and Neukirch identified.

As the flexural wave moves further and further away from the first fracture point, the bend at the apex will grow sharper and sharper until the apex gets to a bend so sharp it once again exceeds the maximum tensile stress, causing a second fracture. As Sandlin cleverly explains: "it is almost as if the spaghetti is trying to straighten itself out, but it can't overcome its own mass" (Sandlin, 2014).

Once the second fracture happens, the process repeats all over again, and the flexural wave will be continuously generated and travel down the strand. This is the reason why spaghetti will sometimes break into 4, 5, or even more pieces.

The spaghetti-snapping phenomenon heavily depends on how far the flexural wave travels. The farther the flexural wave travels, the sharper the angle at the apex will grow, and hence the more likely another fracture will happen. In addition, as the flexural wave travels across the peak of the original arc of the spaghetti before it snaps, the angle at the apex will grow at a much sharper rate compared to if the wave travels through any other sections of the spaghetti. This is why the first ejected piece usually fractures after the flexural wave travels beyond the center of the spaghetti. This explanation also reveals why sometimes the spaghetti doesn't snap into multiple pieces. On the rare occasions when the spaghetti breaks cleanly down the middle, there is no piece long enough for the flexural wave to propagate through and accumulate enough bend at the apex to snap again, therefore resulting in a rare clean break of two pieces.

The End…?

Our dear spaghetti now nears the end of its journey. Physicists have modeled the mechanics of the spaghetti using Kirchhoff's equations, successfully simulated the cascading fracture, and have taken high speed footage at a quarter of a million frames per second. If Feynman is still around today, I'm sure he would be satisfied with all the research done on this kitchen endeavor.

However, this is *still* not the end. Fedem Technologies, an engineering dynamic simulation company, identified a number of limitations with the current research done on cascading fractures: this phenomenon has yet to be studied with varying lengths of rods, speeds, and damping. There still remains quite a large array of areas that have yet to be uncovered about cascading fractures (Fedem, 2014). We still do not have a comprehensive understanding on the nature of flexural waves and cascading fractures.

I myself tried snapping different noodles in the kitchen when I was cooking (without wasting too much food of course). I found even the Asian buckwheat noodle and traditional Chinese rice flour noodles also fracture into multiple pieces. Spaghetti is not the only type that behaves this way -- the relatives of our beloved spaghetti also possess the same properties, and perhaps even more secrets yet undiscovered by physicists.

So the next time you cook spaghetti, snap a strand or two while you wait for the water to boil. Feel the flexural wave travel down the noodle to your fingers and appreciate the quirky behavior of the spaghetti strand. If you have friends over, you can explain to them about flexural waves, maximum tensile stress, and cascading fractures. That will certainly make pasta night a lot more exciting, and our humble spaghetti can at last receive the appreciation it deserves.

And finally, keep your eyes open. Hidden mysteries, undiscovered phenomena, and intriguing surprises hide in every corner in our everyday lives. Stay curious, and be ready to let your mind be illuminated in the most unexpected ways.

About the Author

Stephen Tsung-Han Sher is a Taiwanese international student studying Computer Engineering & Computer Science at USC as of 2015. One of his favorite meals is spaghetti with homemade pasta sauce; he continues to snap at least one strand of spaghetti very time he cooks spaghetti.

List of Potential Multimedia Add-ons

Destin Sandlin's high speed footage on snapping spaghetti, Smarter Everyday

https://www.youtube.com/watch?v=ADD7QlQoFFI

Cascading fracture simulation, Fedem Technology

http://www.fedem.com/services/software/applications/spagfracture

Video footage of Audoly and Neukirch's experiments\

http://www.lmm.jussieu.fr/spaghetti/

http://www.lmm.jussieu.fr/spaghetti/movies-6-more.html

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