The Eureka Phenomena

By Isaac Asimov

In the old days, when I was writing a great deal of fiction, there would come, once in a while, moments when I was stymied. Suddenly, I would find I had written myself into a hole and could see no way out. To take care of that, I developed a technique which invariably worked.

It was simply this-I went to the movies. Not just any movie. I had to pick a movie which was loaded with action but which made no demands on the intellect. As I watched, I did my best to avoid any conscious thinking concerning my problem, and when I came out of the movie I knew exactly what I would have to do to put the story back on the track.

It never failed.

In fact, when I was working on my doctoral dissertation, too many years ago, I suddenly came across a flaw in my logic that I had not noticed before and that knocked out everything I had done. In utter panic, I made my way to a Bob Hope movie-and came out with the necessary change in point of view.

It is my belief, you see, that thinking is a double phenomenon like breathing.

You can control breathing by deliberate voluntary action: you can breathe deeply and quickly, or you can hold your breath altogether, regardless of the body's needs at the time. This, however, doesn't work well for very long. Your chest muscles grow tired, your body clamors for more oxygen, or less, and you relax. The automatic involuntary control of breathing takes over, adjusts it to the body's needs, and unless you have some respiratory disorder, you can forget about the whole thing.

Well, you can think by deliberate voluntary action, too, and I don't think it is much more efficient on the whole than voluntary breath control is. You can deliberately force your mind through channels of deductions and associations in search of a solution to some problem and before long you have dug mental furrows for yourself and find yourself circling round and round the same limited pathways. If those pathways yield no solution, no amount of further conscious thought will help.

On the other hand, if you let go, then the thinking process comes under automatic involuntary control and is more apt to take new pathways and make erratic associations you would not think of consciously. The solution will then come while you *think* you are *not* thinking.

The trouble is, though, that conscious thought involves no muscular action and so there is no sensation of physical weariness that would force you to quit. What's more, the panic of necessity tends to force you to go on uselessly, with each added bit of useless effort adding to the panic in a vicious cycle.

It is my feeling that it helps to relax, deliberately, by subjecting your mind to material complicated enough to occupy the voluntary faculty of thought, but superficial enough not to engage the deeper involuntary one. In my case, it is an action movie; in your case, it might be something else.

I suspect it is the involuntary faculty of thought that gives rise to what we call "a flash of intuition," something that I imagine must be merely the result of unnoticed thinking.

Perhaps the most famous flash of intuition in the history of science took place in the city of Syracuse in third-century B.C. Sicily. Bear with me and I will tell you the story

About 250 B.C., the city of Syracuse was experiencing a kind of Golden Age. It was under the protection of the rising power of Rome, but it retained a king of its own and considerable self-government; it was prosperous; and it had a flourishing intellectual life.

The king was Hieron 11, and he had commissioned a new golden crown from a goldsmith, to whom he had given an ingot of gold as raw material. Hieron, being a practical man, had carefully weighed the ingot and then weighed the crown he received back. The two weights were precisely equal. Good deal! '

But then he sat and thought for a while. Suppose the goldsmith had subtracted a little bit of the gold, not too much, and had substituted an equal weight of the considerably less valuable copper. The resulting alloy would still have the appearance of pure gold, but the goldsmith would be plus a quantity of gold over and above his fee. He would be buying gold with copper, so to speak, and Hieron would be neatly cheated.

Hieron didn't like the thought of being cheated any more than you or I would, but he didn't know how to find out for sure if he had been. He could scarcely punish the goldsmith on mere suspicion. What to do?

Fortunately, Hieron had an advantage few rulers in the history of the world could boast. He had a relative of considerable talent. The relative was named Archimedes and he probably had the greatest intellect the world was to see prior to the birth of Newton.

Archimedes was called in and was posed the problem.

He had to determine whether the crown Hieron showed him was pure gold, or was gold to which a small but significant quantity of copper had been added.

If we were to reconstruct Archimedes' reasoning, it might go as follows. Gold was the densest known substance (at that time). Its density in modern terms is 19.3 grams per cubic centimeter. This means that a given weight of gold takes up less volume than the same weight of anything else! In fact, a given weight of pure gold takes up less volume than the same weight of any kind of impure gold.

The density of copper is 8.92 grams per cubic centimeter, just about half that of gold. If we consider 100 grams of pure gold, for instance, it is easy to calculate it to have a volume of 5.18 cubic centimeters. But suppose that 100 grams of what looked like pure gold was really only 90 grams of gold and 10 grams of copper. The 90 grams of gold would have a volume of 4.66 cubic centimeters, while the 10 grams of copper would have a volume of 1.12 cubic centimeters; for a total value of 5.78 cubic centimeters.

The difference between 5.18 cubic centimeters and 5.78 cubic centimeters is quite a noticeable one, and would instantly tell if the crown were of pure gold, or if it contained 10 per cent copper (with the missing 10 per cent of gold tucked neatly in the goldsmith's strongbox).

All one had to do, then, was measure the volume of the crown and compare it with the volume of the same weight of pure gold.

The mathematics of the time made it easy to measure the volume of many simple shapes: a cube, a sphere, a cone, a cylinder, any flattened object of simple regular shape and known thickness, and so on.

We can imagine Archimedes saying, "All that is necessary, sire, is to pound that crown flat, shape it into a square of uniform thickness, and then I can have the answer for you in a moment".

Whereupon Hieron must certainly have snatched the crown away and said, "No such thing. I can do that much without you; I've studied the principles of mathematics, too. This crown is a highly satisfactory work of art and I won't have it damaged. Just calculate its volume without in any way altering it."

But Greek mathematics had no way of determining the volume of anything with a shape as irregular as the crown, since integral calculus had not yet been invented (and wouldn't be for two thousand years, almost). Archimedes would have had to say, "There is no known way, sire, to carry through a non-destructive determination of volume."

"Then think of one," said Hieron testily.

And Archimedes must have set about thinking of one, and gotten nowhere. Nobody knows how long he thought, or how hard, or what hypotheses he considered and discarded, or any of the details.

What we do know is that, worn out with thinking, Archimedes decided to visit the public baths and relax. I think we are quite safe in saying that Archimedes had no intention of taking his problem to the baths with him. It would be ridiculous to imagine he would, for the public baths of a Greek metropolis weren't intended for that sort of thing.

The Greek baths were a place for relaxation. Half the social aristocracy of the town would be there and there was a great deal more to do than wash. One steamed one's self, got a massage, exercised, and engaged in general socializing. We can be sure that Archimedes intended to forget the stupid crown for a while.

One can envisage him engaging in light talk, discussing the latest news from Alexandria and Carthage, the latest scandals in town, the latest funny jokes at the expense of the country-squire Romans-and then be lowered himself into a nice hot bath which some bumbling attendant had filled too full.

The water in the bath slopped over as Archimedes got in. Did Archimedes notice that at once, or did he sigh, sink back, and paddle his feet awhile before noting the water-slop. I guess the latter. But, whether soon or late, he noticed, and that one fact, added to all the chains of reasoning his brain had been working on during the period of relaxation when it was unhampered by the comparative stupidities (even in Archimedes) of voluntary thought, gave Archimedes his answer in one blinding flash of insight.

Jumping out of the bath, he proceeded to run home at top speed through the streets of Syracuse. He did not bother to put on his clothes. The thought of Archimedes running naked through Syracuse has titillated dozens of generations of youngsters who have heard this story, but I must explain that the ancient Greeks were quite lighthearted in their attitude toward nudity. They thought no more of seeing a naked man on the streets of Syracuse, than we would on the Broadway stage.

And as he ran, Archimedes shouted over and over, "I've got it! I've got it!" Of course, knowing no English, he was compelled to shout it in Greek, so it came out, *"Eureka! Eureka!"*

Archimedes' solution was so simple that anyone could understand it-once Archimedes explained it.

If an object that is not affected by water in any way, is immersed in water, it is bound to displace an amount of water equal to its own volume, since two objects cannot occupy the same space at the same time.

Suppose, then, you had a vessel large enough to hold the crown and suppose it had a small overflow spout set into the middle of its side. And suppose further that the vessel was filled with water exactly to the spout, so that if the water level were raised a bit higher, however slightly, some would overflow.

Next, suppose that you carefully lower the crown into the water. The water level would rise by an amount equal to the volume of the crown, and that volume of water would pour out the overflow and be caught in a small vessel. Next, a lump of gold, known to be pure and exactly equal in weight to the crown, is also immersed in the water and again the level rises and the overflow is caught in a second vessel.

If the crown were pure gold, the overflow would be exactly the same in each case, and the volumes of water caught in the two small vessels would be equal. If, however, the crown were of alloy, it would produce a larger overflow than the pure gold would and this would be easily noticeable.

What's more, the crown would in no way be harmed, defaced, or even as much as scratched. More important, Archimedes had discovered the "principle of buoyancy."

And was the crown pure gold? I've heard that it turned out to be alloy and that the goldsmith was executed, but I wouldn't swear to it.

How often does this "Eureka phenomenon" happen? How often is there this flash of deep insight during a moment of relaxation, this triumphant cry of "I've got it! I've got it!" which must surely be a moment of the purest ecstasy this sorry world can afford?

I wish there were some way we could tell. I suspect that in the history of science it happens *often;* I suspect that very few significant discoveries are made by the pure technique of voluntary thought; I suspect that voluntary thought may possibly prepare the ground (if even that), but that the final touch, the real inspiration, comes when thinking is under involuntary control.

But the world is in a conspiracy to bide that fact. Scientists are wedded to reason, to the meticulous working out of consequences from assumptions, to the careful organization of experiments designed to check those consequences. If a certain line of experiments ends nowhere, it is omitted from the final report. If an inspired guess turns out to be correct, it is *not* reported as an inspired guess. Instead, a solid line of voluntary thought is invented after the fact to lead up to the thought, and that is what is inserted in the final report.

The result is that anyone reading scientific papers would swear that *nothing* took place but voluntary thought maintaining a steady clumping stride from origin to destination, and that just can't be true.

It's such a shame. Not only does it deprive science of much of its glamour (how much of the dramatic story in Watson's *Double Helix* do you suppose got into the final reports announcing the great discovery of the structure of DNA?*), but it hands over the important process of "insight," "inspiration," "revelation" to the mystic.

* I'll tell you, in case you're curious. Nonel

The scientist actually becomes ashamed of having what we might call a revelation, as though to have one is to betray reason-when actually what we call revelation in a man who has devoted his life to reasoned thought, is after all merely reasoned thought that is not under voluntary control.

Only once in a while in modern times do we ever get a glimpse into the workings of involuntary reasoning, and when we do, it is always fascinating. Consider, for instance, the case of Friedrich August Kekule von Stradonitz.

In KekuIe's time, a century and a quarter ago, a subject of great interest to chemists was the structure of organic molecules (those associated with living tissue). Inorganic molecules were generally simple in the sense that they were made up of few atoms. Water molecules, for instance, are made up of two atoms of hydrogen and one of oxygen (H,O). Molecules of ordinary salt are made up of one atom of sodium and one of chlorine (NaCl), and so on.

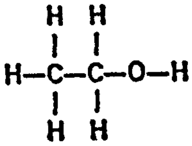
Organic molecules, on the other hand, often contained a large number of atoms. Ethyl alcohol molecules have two carbon atoms, six hydrogen atoms, and an oxygen atom (C_2H_6O); the molecule of ordinary cane sugar is $C_{12}H_{22}O_{11}$, and other molecules are even more complex.

Then, too, it is sufficient, in the case of inorganic molecules generally, merely to know the kinds and numbers of atoms in the molecule; in organic molecules, more is necessary. Thus, dimethyl ether has the formula C_2H_6O, just as ethyl alcohol does, and yet the two are quite different in properties. Apparently, the atoms are arranged differently within the molecules-but how to determine the arrangements?

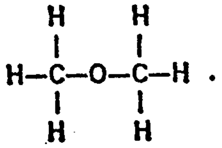
In 1852, an English chemist, Edward Frankland, had noticed that the atoms of a particular element tended to combine with a fixed number of other atoms. This combining number was called "valence." Kekule in 1858 reduced this notion to a system. The carbon atom, he decided (on the basis of plenty of chemical evidence) had a valence of four; the hydrogen atom, a valence of one; and the oxygen atom, a valence of two (and so on).

Why not represent the atoms as their symbols plus a number of attached dashes, that number being equal to the valence. Such atoms could then be put together as though they were so many Tinker Toy units and "structural formulas" could be built up.

It was possible to reason out that the structural formulas of ethyl alcohol and of dimethyl ether were ıs



$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-O-H$



$H-\underset{H}{\overset{H}{C}}-O-\underset{H}{\overset{H}{C}}-H$.

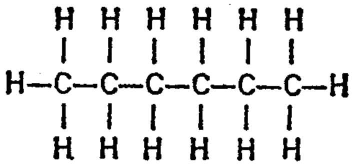
In each case, there were two carbon atoms, each with four dashes attached; six hydrogen atoms, each with one dash attached; and an oxygen atom with two dashes attached. The molecules we're built up of the same components, but in different arrangements.

Kekule's theory worked beautifully. It has been immensely deepened and elaborated since his day, but you can still find structures very much like Kekule's Tinker Toy formulas in any modern chemical textbook. They represent oversimplifications of the true situation, but they remain extremely useful in practice even so.

The Kekule structures were applied to many organic molecules in the years after 1858 and the similarities and contrasts in the structures neatly matched similarities and contrasts in properties. The key to the rationalization of organic chemistry had, it seemed, been found.

Yet there was one disturbing fact. The well-known chemical benzene wouldn't fit. It was known to have a molecule made up of equal numbers of carbon and hydrogen atoms. Its molecular weight was known to be 78 and a single carbon-hydrogen combination had a weight of 13. Therefore, the benzene molecule had to contain six carbon-hydrogen combinations and its formula had to be C_6H_6.

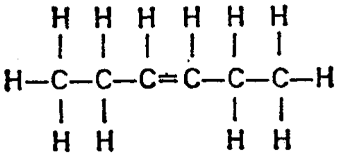
But that meant trouble. By the Kekule formulas, the hydrocarbons (molecules made up of carbon and hydrogen atoms only) could easily be envisioned as chains of carbon atoms with hydrogen atoms attached. If all the valences of the carbon atoms were filled with hydrogen atoms, as in "hexane," whose molecule looks like this --



$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H$

the compound is said to be saturated. Such saturated hydrocarbons were found to have very little tendency to react with other substances.

If some of the valences were not filled, unused bonds were added to those connecting the carbon atoms. Double bonds were formed as in "hexene" --



$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\overset{H}{C}=\overset{H}{C}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H$

Hexene is unsaturated, for that double bond has a tendency to open up and add other atoms. Hexene is chemically active.

When six carbons are present in a molecule, it takes fourteen hydrogen atoms to occupy all the valence bonds and make it inert-as in hexane. In hexene, on the other hand, there are only twelve hydrogens. If there were still fewer hydrogen atoms, there would be more than one double bond; there might even be triple bonds, and the compound would be still more active than hexene.

Yet benzene, which is C_6H_6, and has eight fewer hydrogen atoms than hexane, is less active than hexene, which has only two fewer hydrogen atoms than hexane. In fact, benzene is even less active than hexane itself. The six hydrogen atoms in the benzene molecule seem to satisfy the six carbon atoms to a greater extent than do the fourteen hydrogen atoms in hexane.

For heaven's sake, why?

This might seem unimportant. The Kekule formulas were so beautifully suitable in the case of so many compounds that one might simply dismiss benzene as an exception to the general rule.

Science, however, is not English grammar. You can't just categorize something as an exception. If the exception doesn't fit into the general system, then the general system must be wrong.

Or, take the more positive approach. An exception can often be made to fit into a general system, provided the general system is broadened. Such broadening generally represents a great advance and for this reason, exceptions ought to be paid great attention.

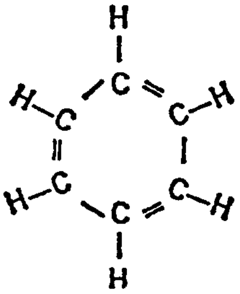
For some seven years, Kekule faced the problem of benzene and tried to puzzle out how a chain of six carbon atoms could be completely satisfied with as few as six hydrogen atoms in benzene and yet be left unsatisfied with twelve hydrogen atoms in hexene.

Nothing came to him!

And then one day in 1865 (he tells the story himself) he was in Ghent, Belgium, and in order to get to some destination, he boarded a public bus. He was tired and, undoubtedly, the droning beat of the horses' hooves on the cobblestones, lulled him. He fell into a comatose half-sleep.

In that sleep, he seemed to see a vision of atoms attaching themselves to each other in chains that moved about. (Why not? It was the sort of thing that constantly occupied his waking thoughts.) But then one chain twisted in such a way that head and tail joined, forming a ring-and Kekule woke with a start.

To himself, he must surely have shouted "Eureka," for indeed he had it. The six carbon atoms of benzene formed a ring and not a chain, so that the structural formula looked like this:



To be sure, there were still three double bonds, so you might think the molecule had to be very active-but now there was a difference. Atoms in a ring might be expected to have different properties from those in a chain and double bonds in one case might not have the properties of those in the other. At least, chemists could work on that assumption and see if it involved them in contradictions.

It didn't. The assumption worked excellently well. It turned out that organic molecules could be divided into two groups: aromatic and aliphatic. The former had the benzene ring (or certain other similar rings) as part of the structure and the latter did not. Allowing for different properties within each group, the Kekule structures worked very well.

For nearly seventy years, Kekule's vision held good in the hard field of actual chemical techniques, guiding the chemist through the jungle of reactions that led to the synthesis of more and more molecules. Then, in 1932, Linus Pauling applied quantum mechanics to chemical structure with sufficient subtlety to explain just why the benzene ring was so special and what had proven correct in practice proved correct in theory as well.

Other cases? Certainly.

In 1764, the Scottish engineer James Watt was working as an instrument maker for the University of Glasgow. The university gave him a model of a Newcomen steam engine, which didn't work well, and asked him to fix it. Watt fixed it without trouble, but even when it worked perfectly, it didn't work well. It was far too inefficient and consumed incredible quantities of fuel. Was there a way to improve that?

Thought didn't help; but a peaceful, relaxed walk on a Sunday afternoon did. Watt returned with the key notion in mind of using two separate chambers, one for steam only and one for cold water only, so that the same chamber did not have to be constantly cooled and reheated to the infinite waste of fuel.

The Irish mathematician William Rowan Hamilton worked up a theory of "quaternions" in 1843 but couldn't complete that theory until he grasped the fact that there were conditions under which p x q was not equal to q x p. The necessary thought came to him in a flash one time when he was walking to town with his wife.

The German physiologist Otto Loewi was working on the mechanism of nerve action, in particular, on the chemicals produced by nerve endings. He woke at 3 A.M. one night in 1921 with a perfectly clear notion of the type of experiment he would have to run to settle a key point that was puzzling him. He wrote it down and went back to sleep. When he woke in the morning, he found he couldn't remember what his inspiration had been. He remembered he had written it down, but he couldn't read his writing.

The next night, he woke again at 3 A.M. with the clear thought once more in mind. This time, he didn't fool around. He got up, dressed himself, went straight to the laboratory and began work. By 5 A.m. he had proved his point and the consequences of his findings became important enough in later years so that in 1936 he received a share in the Nobel prize in medicine and physiology.

How very often this sort of thing must happen, and what a shame that scientists are so devoted to their belief in conscious thought that they so consistently obscure the actual methods by which they obtain their results.