The World Keeps on Changing

The science of transformation, mobility and tadpoles

It doesn't matter
whether you're talking about a material,
a creature, or a human being,
immortality is said to be impossible.
Everything changes.
So perhaps studying the mechanics of
change can help us uncover something of
the blueprint of our world.

Methods and purpose of rheology
Everybody's a rheologist

Do you remember the heat this last summer? Temperatures were in the 90s almost every day, and sometimes when you stepped on asphalt it seemed like liquid. It was this kind of day when I visited Nippon Paint Co., Ltd.,which was somehow appropriate given the discussion we had on how glass can flow like liquid.

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Rheology is the science of the mobility and transformation of materials. It can be applied wherever materials exhibit the properties of flow and transformation…but if we say this, people might think we're just talking gibberish.

"Rheology can be a 'touchy' subject." Nippon Paint's Takanobu Ueda, the recipient of the Society of Rheology 1998 Japan Research Award, tried to explain this unfamiliar branch of study with clever, humorous expressions.

"When you touch an object, it's normal to use a little force to see how solid it is. This, in fact, is rheology. When we bite into pasta, we either say it's al dente or it's overcooked. That's rheology, too. Rheology is an attempt to scientifically interpret, or quantify, what we feel using our five senses."

Rheology is a scientific branch of study somewhere in between fluid dynamics and the mechanics of solids. It works to quantify elasticity, malleability, fluidity, viscosity, and other elusive properties of materials.

Why would we want to quantify our senses? Well, it might reveal some professional secrets. For example, if you work at a gas station long enough you can easily tell the condition of a car's oil just by touching it. This is the kind of skill researchers are now working to analyze at the science level.

"I was once contacted by a food manufacturer and told of a very interesting situation. About a hundred of technicians and engineers gathered around a famous chef named Tomitoku Shu. Then, while he was beating an egg, they tried to quantify all of his actions, including how many times he beat the egg, his exact speed, etc. But even if a machine were constructed that could perfectly mimic his physical procedures, the taste would still be different. It was at this point I brought up the subject of rheology."

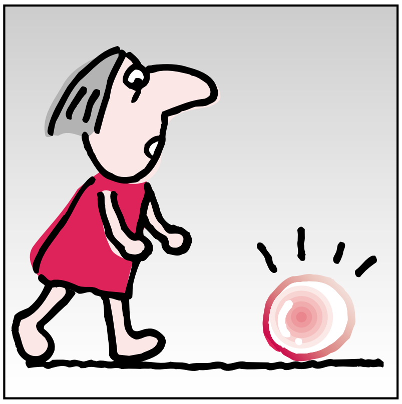
Although Mr. Shu's movements can be understood and quantified on a surface level, it is important to scientifically pursue what he was *feeling* during his actions. The purpose of rheology is:

1.) To quantify information we receive from our five senses and apply it toward automation and standardization,
2.) To understand the mechanism that gives materials their unique characteristics of viscosity, elasticity, fluidity, etc., and
3.) Based on analysis and experiments in materials production, apply what was learned in parts 1 and 2 to create new materials and products.

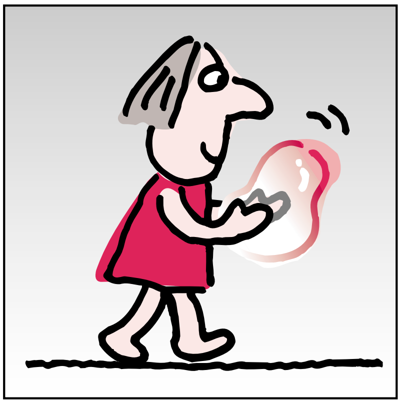
"If we study the influence of vibration on various materials, we can learn how to produce materials strong enough to withstand powerful vibration. Interestingly, a mechanical engineering researcher once asked us to apply the principles of rheology to help develop a

Takanobu Ueda, manager of the Materials Properties Research and Technical Information Center of Nippon Paint Co., Ltd., is active in many fields beyond paint and is a noted authority on rheology. In May 1998 he was presented with the Society of Rheology Japan Research Award for his study of viscoelastic properties of disperse system using FT-RM. FT-RM is a new method for measuring frequency dependence of G' and G", using rheometer oscillated by multifrequency wave.

Where does a rheologist go?



I travel all over the world.
There’s nothing I haven’t seen.



Nothing surprises me
because I’ve seen and done it all.

robot able to hold a sponge gently, without deforming it.”

Mr. Ueda is working to apply the principles of rheology to many fields, including food (how cookies and cakes rise, how we sense the texture of mayonnaise), cosmetics (best viscosity to increase sales) and medicine (blood viscosity as a diagnostic tool, new medical products). From his initial work studying paint, Mr. Ueda is now happily playing in all kinds of different fields.

“People that work in rheology don’t always live in their lab coats. When we get together to drink sake, there’s always someone who will start talking about its viscosity. And when we mix together mayonnaise and soy sauce as a dip for dried squid, we observe how difficult it is to combine these two ingredients. Is this caused by a viscosity problem? It’s often this kind of casual situation that inspires the research we end up presenting at conferences.”

Macromolecular composition and transformation

Spaghetti model

The field of rheology is actually quite old, tracing its origins back to 1929. It was inspired by a man named Mr. Bingham, who was keenly interested in the flow of paint. The original purpose of rheology was to investigate the characteristics of macromolecules from the standpoint of physical motion, not chemical composition. But around ten years ago we began to see the limits of petrochemistry, which until then had offered an almost ultimate understanding of the chemistry of macromolecules. This is what prompted us to begin applying the principles of rheology.

Petrochemical research has resulted in the development of many dream materials, including synthetic polyester, rayon and more. But most of the materials that can be created based on traditional theories have already been produced, and current research focuses more on how to utilize them. This is similar to food, where we have wide access to ingredients from all over the world and now need a professional chef to create some a new menu.

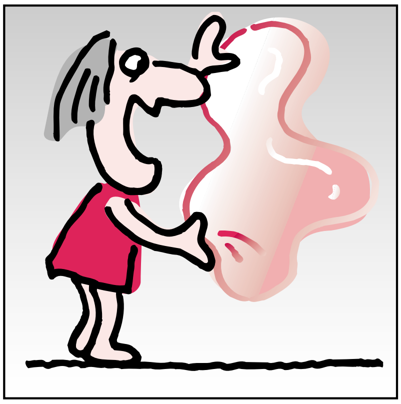
Let’s take a closer look at macromolecules, a la Italiano. The macromolecules are extremely heavy, having a molecular weight of over 100,000. Mr. Ueda used a unique analogy for talking about their viscosity—spaghetti.

- *Spaghetti Neapolitan (high viscosity)*
  “Cold spaghetti Neapolitan is hard to eat because when you stick in your fork to pick it up, everything comes up together. It has extremely high viscosity, almost like a thick gel.”
- *Soup spaghetti (low viscosity)*
  “This has low viscosity and doesn’t stick together at all. In fact, you can easily pluck out a single strand. Heating macromolecules that are in liquid form results in this kind of situation.”
- *Spaghetti salad (extremely low viscosity)*
  “If you want to add spaghetti to a salad, you have to cut it in half to make it combine easily with other ingredients. This is analogous to cutting a molecular weight in half to reduce viscosity.”

Let’s examine how plastic, a common macromolecule, softens at high temperatures.

“Think about the structure of plastic as being like panty hose, with many tiny threads tightly woven together. Initially, the threads make the plastic seem hard and solid, but if you remove them one by one it steadily becomes softer. In other words, its hardness decreases. Eventually you will be left with extremely soft panty hose that has little sense of solidity. If you unweave all the threads in panty hose, they behave like a liquid and flow everywhere, like plastics that melt when heated. Wood, on the other hand, is so tightly bound together it never softens—much less enters a liquid phase.”

Research on macromolecules has led to



Why does this thing behave like it does?

*There are some things I have not seen.
Using my own hands, I reach out
toward an unknown world.*

some unexpected inventions. For example, have you ever pulled a polyethylene bag off a roll in a supermarket? These bags were produced by rapidly stretching thin sheets of polyethylene to their maximum length to create an extremely thin material that is very strong in the direction in which it was pulled. The thicker parts are spread and pulled until they become extremely thin making the bag exceptionally strong in the vertical direction in which it was rolled—ideal for carrying heavy items. Since molecules are only stretched in the vertical direction, the horizontal direction will be relatively weak, making it easy to rip a single bag from the roll.

Compounds that can change

Ball-shaped liquids and solids that flow

Up to this point we have been discussing macromolecules. Recently, however, rheology has entered into a new phase.

“We have nearly completed our research on macromolecules, and our focus is changing to the disperse system which is the state where two dissimilar materials are combined. Common examples include bread, a mixture of air and solid, and mayonnaise, a mix of water and oil. Depending on conditions, these mixtures can flow easily or remain firm and solid, which means there will be some unexpected movement characteristics to investigate.”

Can we apply our panty hose analogy to these materials?

“No. In this case, it depends on how the individual particles disperse, whether they’re jammed in close together or spaced far apart. Good examples of this kind of material are *kawara*, the heavy tiles used on Japanese roofs, and the underground water pipes made out of concrete. If you combine sand and water but don’t stir it fast enough, the mixture becomes hard. But the faster you stir it, the softer it becomes. We call this characteristic structural viscosity.”

Other examples of this are potter’s clay, and paint. If you stir paint vigorously, it becomes less viscous and is easier to brush. Letting paint sit increases its viscosity, which prevents it from running.

“We sometimes experience the exact opposite phenomenon, which is as if you treat something gently, it responds gently, like a woman. Singing sand, for instance, has a very organized distribution of particles. If you step on it heavily, it becomes hard like a solid. If you step on it gently, it flows like a liquid.”

Sometimes liquid, sometimes solid... As I pondered this Mr. Ueda brought out two balls, the kind sometimes packaged with children’s science magazines. Both were about the size of a superball, and felt identical when you held them. But when I dropped them on a table, one bounced quite high while the other did not bounce at all.

“The ball that doesn’t bounce absorbs energy whenever there is an abrupt change of motion. This indicates it is not a bounce material but rather a high viscosity material. Some people might call it a liquid, and say ‘that’s why it doesn’t bounce.’”

But how can a solid be a liquid? What is going on here?

“The famous rheologist Takayoshi Matsumoto wrote a book in which he mentions the Biblical Old Testament prophetess Deborah, who said that through the power of God, ‘Everything can move, even mountains.’ From the point of view of rheology, this is true—everything moves, even if it’s as big and solid as a mountain. For example, glass melts if you heat it to very high temperatures. Replacing heat with time, if you observe glass over hundreds of millions of years it appears to flow like a liquid. In other words, if human life spans were a billion years, we would perceive glass as a slow-flowing liquid. So the same material can be considered both a liquid and a solid. I think what attracts me the most to rheology is looking at natural phenomena from vastly different points of view.”

Metamorphosis and the mechanics of motion

The strategy of a tadpole

The way you observe something can totally change its appearance. When we talk about rheology it reminds me of Reynolds Number, the research specialty of Mr. Keiji Kawachi of Tokyo University's Research Center for Advanced Science and Technology. The connection was not simply because rheology and Reynolds both start with r.

Reynolds Number is used to describe the flow characteristics of a material. While insects and humans share the same air, the Reynolds Number for each is different, which means we feel air differently. For insects, air is very sticky and has a high viscosity. And although their wings are not streamlined, they are well suited for sticky air. Mr. Kawachi's main point was: "If we want to create a micromachine, we cannot apply common sense based on objects measured in meters."

From his analysis of tadpole movement, Mr. Kawachi unearthed some key findings on metamorphosis. Though it was not the main focus of his research, we asked him about metamorphosis because of its connection to the science of change.

"A biologist once asked me to study the movement of a tadpole, so I calculated the change in the efficacy of movement that would occur as it grew legs. After several experiments in both 2-D and 3-D, however, we proved that growing legs does not significantly alter the efficacy of movement. This implies their legs are positioned in a place where the effects of water flow are minimal."

How does this benefit the tadpole?

"It doesn't need to relearn how to swim, use its tail, or stop, which reduces the demands on the tadpole's nervous

Keiji Kawachi is a professor at Tokyo University's Research Center for Advanced Science and Technology. From 1992-97 he served as director of the Kawachi Millibioflight Project, part of the ERATO (Exploratory Research for Advanced Technology) sponsored by the Japan Science and Technology Corporation. A documentary film of his work titled "Bigger need not be better—Small bodies in motion" was awarded the First Prize in the Technology and Research Category of a Festival de Biarritz 98 in France (for industrial films). Mr. Kawachi was born in Kanagawa Prefecture in 1947.

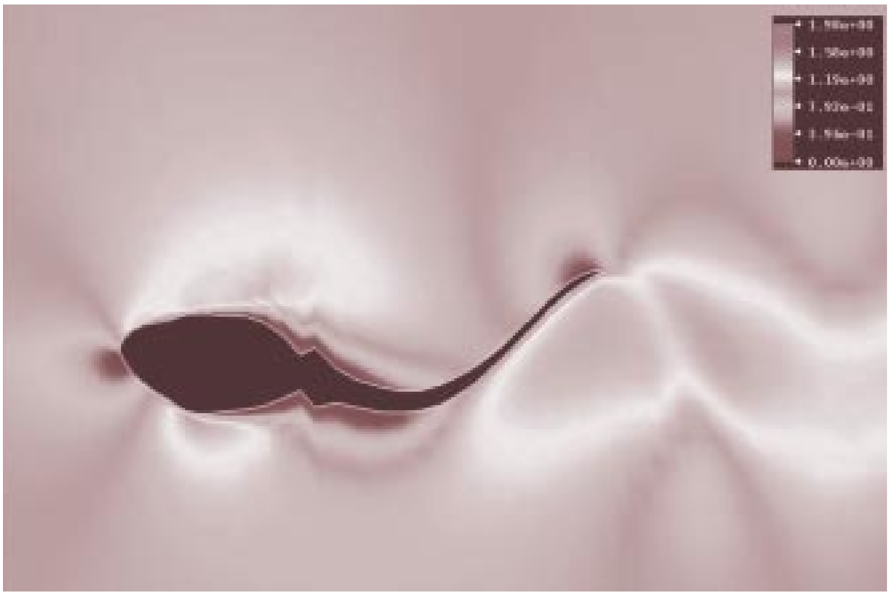
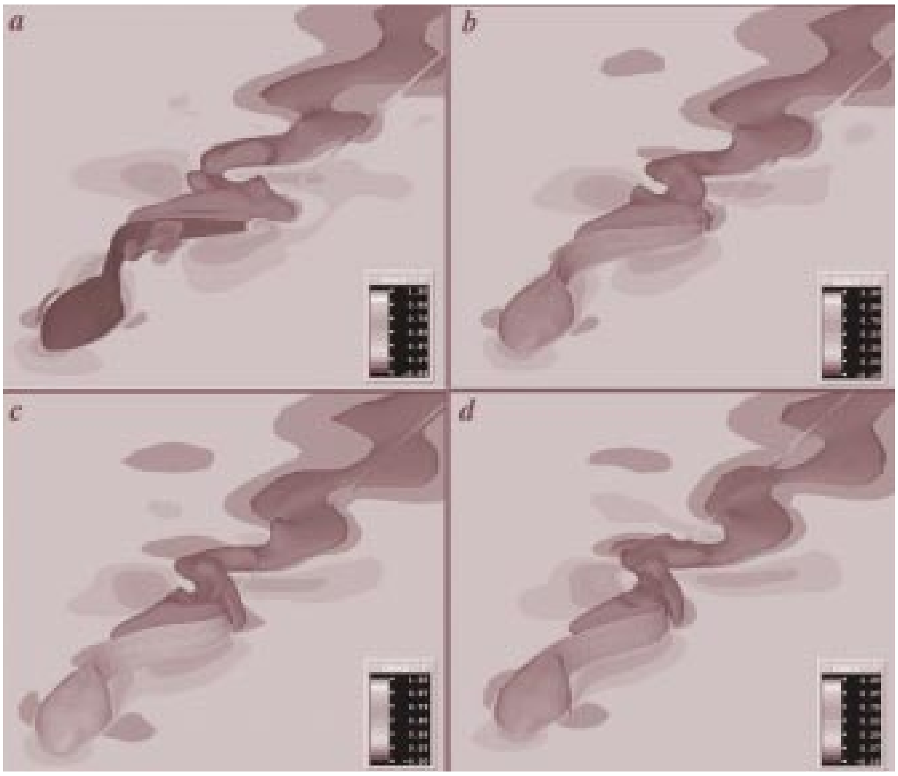


Image created by Dr. Hao Liu, Department of Mechanical and Systems Engineering, Nagoya Institute of Technology. Dr. Liu also created the image on page 7.



system. If this were not the case, it would have to relearn how to swim every time its legs grew longer. For contrast, we also calculated the flow characteristics for a fish, and compared them to a fish with legs. We found that no matter where we added legs the resistance to movement increased, which changed the efficacy of movement."

So tadpoles must live with a shape that's far from beautiful simply because they eventually want to grow legs? Are legs more important than having a beautiful streamlined shape?

"If tadpoles were to live their entire lives in the water, their body shape would not be very comfortable from the point of view of energy use. Still, why do they go through metamorphosis, being born in the water and later coming on land? That I don't know. Maybe the only answer is that this kind of creature survived while others did not."

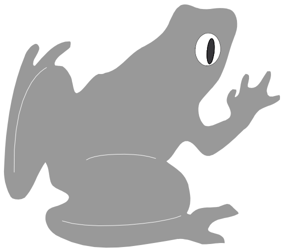
From water to land…what made them dare to choose such a difficult path?

"If you want to change your living environment, body parts you once needed for movement in your old environment may no longer be necessary. They may even deter it. In the water, a tail clearly provides the best kind of limb for locomotion. If you try and use only legs or hands or arms, you will surely lose in a competition with the aquatic professionals. On the other hand, if you ascend a hill on the land by jumping with legs, you don't need a tail. Crocodiles and alligators have both tails and legs, which might lead us to believe they aren't well suited for either water or land. But since they are physically strong and live in swampy areas, which are neither land nor water, they were able to survive."

If we were to make a robot for use on both water and land, would it need to transform itself like the characters on current children's TV shows? All creatures are vulnerable during the transformation process and if they change too slowly, their enemies can destroy them. This is why caterpillars surround themselves with a hard chrysalis and cicadas go through metamorphosis inside a hard shell. And tadpoles?

"During the time they live in water, they are preparing for a land lifestyle, which means they also need legs. Their strategy for survival, whether on water or land, is a bit precarious."

If we take this to extremes and consider it from the point of view of evolution, creatures that left the ocean to live on land must have had even more difficulty.



Does the tadpole know something?

"It is often said that the development of an individual reflects the entire history of the evolution of its species. It's not clear, however, that frogs represent the evolution of all creatures that made the move from water to land. This is not my field, and even among biologists I understand there is much argument about evolution. The biggest question I have is about the changes from gills to lungs, and growing legs and hands. Why did these changes occur over about the same time period for so many different species? Many people think natural selection weeded out species that could not survive, while some scientists say the power of will was involved."

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Over the years, Mr. Kawachi's research evolved from the investigation of movement to the study of insect nerves. We asked him why newborn insects can fly immediately, while birds have to learn?

"It's probably because they have some kind of basic control through their nervous systems that's innate. Have you ever captured a dragonfly by moving your finger in a circular motion (which makes it too dizzy to fly away) and then just picking it up? In the laboratory, if we put zebra stripes in front of a fly it will change the angle of its wings or stretch its legs depending on the exact pattern. What I really want to do is uncover the secrets of the insects. I wish I had as many eyes as a fly."