Physics for the 21st Century

Unit 8: Emergence in Quantum Matter

Paul Chaikin and Piers Coleman

> PIERS COLEMAN: *Reductionism is the idea that to understand the world in which we live, you break it down into its constituent parts. You learn the basic laws that control matter on its very smaller scales and once you know that, you'll know everything and you'll immediately understand the universe in which we live.*
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> *But reductionism is not enough. As matter comes together it develops new kinds of structures, new forms of collective motion. We form crystals, a snowflake for example, we form superconductors, and to those properties, we call them emergent.*
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> PAUL CHAIKIN: *Emergence is you. Life, that's an emergent phenomenon that's well beyond from we can understand.*

A big question is, "Are there principles that govern emergent phenomena?" That is the question that Paul Chaikin at New York University and Piers Coleman at Rutgers University are both trying to answer.

Chaikin, an experimentalist, tries to explain emergent phenomena by creating simpler analagous models. He uses some unorthodox and surprising materials.

> PAUL CHAIKIN: *M & M's it turns out are great! They taste good. They're cheap. And before you try and tackle life, you'd like to know how particles come together and organize in a simpler way. And then you want to build upon that.*

Coleman, on the other hand, is a theoretical physicist. He attempts to explain the strange emergent behaviors that new materials display when they are brought to what is known as a quantum critical point.

> PIERS COLEMAN: *This is literally the frontier beneath our nose. Each new material is like its own mini universe of behavior. Which direction do you go in this multiverse of possibilities when you can combine literally any element with another one?*

With two different approaches, these physicists are both attempting to make sense of the complex interactions of the many. It is the challenge of emergence.

Part I: Sweet Emergence

Paul Chaikin

> PAUL CHAIKIN: *The biggest question is what are the organizational principles that nature uses for things. But I mean before you try and tackle life, you'd like to know how particles come together and organize in a simpler way and then you want to build on that.*

Paul Chaikin of New York University likes simple experiments. And one well-known series of experiments that he conducted involved packing problems.

It has always been thought that spheres are the optimal shape when it comes to packing. That ordered spheres at 74% packing density and random spheres at 64% density was the best packing that as can be achieved. Chaikin decided to put this to the test. Instead of spheres, he used M&M's, which are ellipsoids.

> PAUL CHAIKIN: *The random packing of ellipsoids hadn't been tested before. And since in those days I had this habit of having lunch every day of coffee and M & M's, we decided -- well, if we know how spheres pack already -- then why not try ellipsoids.*
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> *And so M&M's -- it turns out are great. They taste good. They're cheap. They're all the same size. And it was the easiest shape past spheres. It is just a simple modification of a sphere.*

Because an ellipsoid is a simple modification of a sphere, Chaikin thought it was likely that the M&M's would pack to the same density as spheres. So it came as a surprise when one of his students found a much greater packing fraction for M&M's.

> PAUL CHAIKIN: *I said that's just wrong, I can prove it to you. So what I did is, I just drew for myself a dense packing for spheres, and if I grab the top of the box and pull it down, it will just distort the whole shape, and these circles will become ellipses, as they are over here. So it distorts the shape of all of the spheres, and it distorts the shape of the box. So the volume fraction for the ellipsoids is the same as for spheres.*
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> *So I was going to tell my student that he was fired, that he should get another job because he does not know how to do the measurement. But before I went to do that I said, "Well that's for when they're ordered, and maybe it's different when they're random." So what I did is, I just drew for myself sort of a random packing. I thought I'd get the same answer, but when I went and I simply did the same trick as before, whereas all of the spheres look stable, every ellipse doesn't look stable. The more you look at it the more unstable it looks. And so if you study it for a little while you*

> *immediately see that what's wrong is that this particle is clearly held in place rigidly by its three neighbors, but this particle, the yellow particle, is not. There's a force from contact between the blue and the yellow over here. That will give you a torque and it can now rotate into this void and therefore pack more densely.*

The way that Chaikin simplified the problem even further, by writing a computer model, is a reductionist technique, showing that emergence and reductionism are not mutually exclusive.

> PAUL CHAIKIN: *You have to be reductionist to some extent. You have to understand the fundamental interactions that you're dealing with before you deal with the bigger problem. Emergence comes from the fact that you know the elementary properties of the particles, the materials you're dealing with, but you get emergent things that you don't expect from those properties. On the other hand, you have to be able to take the thing apart, to take the idea apart or the matter apart, in order to see what fundamentally is going on. Then you sort of start putting it back together, and you see how the properties that you found interesting to begin with, how they came about.*

So why do we care? Aside from improving practical applications like packing grains and pharmaceuticals, this discovery was not just about how particles pack. But it was new physics, new knowledge, that can serve as a building block for tackling more complicated emergent phenomenon.

The dense packing of M&M's emerges with hundreds or thousands of particles, but when it comes to materials comprised of atoms or molecules, the number of particles that are interacting with one another goes up to 10 to the 24 and beyond.

> PAUL CHAIKIN: *And one of the things that emergence sort of tells us is as you go from one scale to the next, from one, from ten, to a thousand, to a million, to Avogadro's number, you have to think about things differently. There are emergent phenomena on each of those different scales.*

In addition to continuing his work on packing problems, Chaikin has also been exploring emergent phenomena through other experiments with colloids.

Colloids are mixtures of two substances where one substance is dispersed evenly throughout another.

Milk, which has liquid butter fat globules inside a water-based fluid is an example of a colloid.

Chaikin uses colloids that consist of a viscous fluid with tiny plastic particles inside.

> PAUL CHAIKIN: *With colloids you can see every single particle, and track how it moves, and see how things arrange, see what the dynamics are, and watch it, which is something that you can't do, and you probably never will be able to do with atoms or molecules. So it really gives you lots of insight into what's going on.*

One experiment with colloids was a replication of a famous film created over thirty years ago by renowned physicist G.I Taylor.

> G.I. TAYLOR [FROM FILM]: *Low Reynolds number flows are those in which inertia…*

In it, Taylor demonstrates what is known as a low Reynolds number, which is a measure in fluid mechanics of how viscous something is as well as how fast it is going.

> PAUL CHAIKIN: *Something that's very viscous, like honey, if you move slowly through honey, it's what's called low Reynolds number. So there's this well-known problem, that at low Reynolds number, that is for slow motion in viscous fluid, the motion is reversible.*
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> G.I. TAYLOR [FROM FILM]: *Here are two concentric cylinders . . .*
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> PAUL CHAIKIN*: There's a beautiful demonstration of it by G.I. Taylor, where he takes two concentric cylinders, with a viscous fluid between them.*
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> G.I. TAYLOR [FROM FILM]: *Into this space I introduce some dye . . .*
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> PAUL CHAIKIN*: He winds the inner cylinder three times, four times one way.*
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> G.I. TAYLOR [FROM FILM]: *The dye seems to mix as a drop of milk mixes when it is stirred into a cup of tea . . .*
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> PAUL CHAIKIN: *And then he winds it back four times . . .*
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> G.I. TAYLOR [FROM FILM]: *Now I reverse the direction . . .*
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> PAUL CHAIKIN: *And the drop of ink reappears . . .*
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> *It's an amazing movie. Anybody that hasn't seen it has to see it.*
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> G.I. TAYLOR [FROM FILM]: *This may lead to some surprising situations,*

> *which might almost make one believe that the fluid has a memory of its own.*
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> PAUL CHAIKIN: *And that's sort of remarkable. It's just sort of remarkable, because most of the things we see in our life is not low Reynolds number, it's high Reynolds number.*

Chaikin's colleagues David Pine and Jerry Gollub decided to recreate Taylor's experiment but instead of using ink, they used small plastic particles inside a viscous fluid.

Like G.I Taylor, they placed their colloid, the fluid and the particles, inside a couette cell, which consists of a cylinder with another cylinder inside it. They then could shear the fluid by rotating the inner cylinder back and forth, oscillating the fluid to see what effect this had on the plastic particles and how they were arranged.

> PAUL CHAIKIN: *And one of the things that's interesting is one of the forefronts of understanding the many body problem, of understanding emergence, of understanding what happens for collections of particles is not what their ground state is, is not what their equilibrium state is. But we really lack knowledge of an organizing principle of what happens when you drive something, when you drive a system, which dissipates energy, which this system does.*
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> *I mean every day, the temperature changes cyclically, and every day the sun comes on and off because it's driven. So this may well be the way that life started. And it may well be that you learn something from this system about the origin of life . . . probably won't, but I don't think the experiment had been tried before so it's worth doing.*

When Pine and Gollub ran this experiment they thought that rotating the cylinder would shear the fluid, causing some particles to collide. Those particles would then be displaced when the cylinder was rotated back to its original position. They also thought that the more they rotated the cell, the more likely it was that collisions would occur.

But what they found was something unexpected. When they rotated the cell past a certain point, shearing the fluid above a certain threshold, some particles would collide and upon rotating the cell back those particles would be displaced from their original position. But when the cell was rotated below that threshold moved around for a certain amount of time and then, they just stopped.

> PAUL CHAIKIN: *The fact that they saw a threshold really, really bothered me. I just didn't understand it at all. And so I worried about it, and I worried about it for a while. So I went and I wrote a little program on my*

> *computer.*

The program that Chaikin wrote was a very straightforward two-dimensional model of the experiment. He placed particles randomly and wrote a simple rule that when the system sheared, if the particles touched then they will be displaced and in a new position when he cycles the system back. If a particle is not close enough to another then it will return to the same position as before.

Chaikin ran this model with different degrees of shearing to see if it would reproduce the results in Pine and Gollub's experiment.

> PAUL CHAIKIN: *So here are the two simulations. If we strain it by three, compared to two, we get very different behaviors.*
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> *This is strobed. So we're only looking at what happens after each shear. You note that a lot of particles are not moving here, but they get infected from particles that are moving around them that are being displaced. And you notice the activity here keeps up, whereas the activity here is decaying with time. Until finally this one below the threshold strain actually stops. It organizes itself so the particles are in configurations where the shear no longer causes any encounters of the particles.*
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> *They return precisely to where they started, and the motion is dead here. And the system has organized itself by that.*
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> *You can tell, for example, that in this case where it stopped. This was the initial configuration, and you see particles are essentially random here and all sorts of different arrangements here, whereas after it stops they've arranged themselves so they've spread out. And although it's difficult to see the correlations here, these configurations are such that when you shear, okay, the particles won't encounter. And one of the ways you can sort of see that is they've almost arranged in sort of strings that go up in this direction, so that when you shear it, this spreads them apart, rather than compresses them.*
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> *That's really emergence. That's without knowing anything. Just the random motion of these particles, and the fact that it's irreversible, that they come back to a different position is enough to organize it. That is really an emergent phenomenon, and it's something I'd never seen before.*

Building on some of this work, Chaikin now is adding levels of complexity to these driven colloidal systems, hoping to learn more about the rules that govern collective behavior.

> PAUL CHAIKIN: *Doing things at room scale, lab scale, you learn a lot. Physics is, essentially, about discovering things about nature that are*

broadly applicable. And if you find some fundamental organizing principles, they often are useful in many many many different contexts. If, I happen to stumble on the origin of life, I won't mind.

Part II: Quantum Emergence

Piers Coleman

So what other approaches exist to explain complex emergent phenomena? Phenomena like superconductivity.

> PIERS COLEMAN: *Superconductors are a very special class of metal in which the electricity flows without resistance at very low temperatures.*
>
> *Superconductivity is a wonderful example of emergent behavior because it's a property of matter that you wouldn't anticipate from the microscopic properties of the ways electrons interact with each other.*

For many physicists, the goal is to find materials that will superconduct at higher temperatures, allowing for an explosion of practical applications such as the transmission of electricity without loss.

In their quest to find room temperature superconductors, experimentalists are combining metals and creating new materials. But with so many possible combinations of elements, experimentalists work with theorists like Piers Coleman at Rutgers University to help them focus their research.

> PIERS COLEMAN: *I work with experimental physicists to try to understand the experiments they're doing and to develop models that explain the emergent behavior that they're seeing in their new crystals, in their new measurements.*
>
> *Let's talk a little bit about the key quantum mechanical features in this system.*

But Coleman's work is not about finding a high temperature superconductor, it is about coming up with the rules of collective behavior that govern superconductivity and other emergent phenomena.

> PIERS COLEMAN: *The superconductor's an example of an expected way we could change the future. I see myself, I see my field as being connected with materials and applications that have the potential to change the future in ways that we can't begin to expect to know.*
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> *And the canvas that we work with is the canvas of the periodic table. We have something like 92 different elements to play with. The amazing thing is that, because of emergence, when we put those atoms together they*

> *develop new properties, not just superconductivity but various other emergent properties that fascinate us. This is literally the frontier beneath our nose. And what we'd like to do is to understand the principles that govern that emergent collective behavior.*

The idea is that there are rules of collective behavior that can be applied universally.

To come up with these rules, physicists need to experiment with materials when they display such behavior. One way to do this is to induce them towards a critical point.

A critical point is the point at which the boundary that separates two stable states of matter disappears. H2O, for instance has three states of matter: liquid, in the form of water, solid, in the form of ice and gas in the form of steam. This is a diagram of those phases, which in and of themselves are examples of emergence.

As you can see there are boundaries between these three phases depending on the pressure and temperature. When we look at the boundary between the liquid phase and the gas phase, it does not continue forever but stops at a critical point in the phase diagram. This critical point reflects the fact that at high pressure and high temperature, it is impossible to distinguish between the liquid and gaseous phases and H_2O enters a different supercritical phase of matter.

> PIERS COLEMAN: *If you look at water at its critical point, it goes dark. And the reason it goes dark is the fluctuations of density expand on longer and longer length scales, they become correlated. They become so correlated that they actually start to scatter light. This is called critical opalescence. So this same opalescent phenomena occurs at all critical points. And it's an example of matter forgetting about its microscopic physics.*
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> *And what we're discovering more and more is that critical points seem to be more and more the linking idea for the periodic table. They are kind of the portals between these different multiverses and we discover that when we can tune a state of matter close to a critical point, it seems to nucleate many new emergent states of behavior, and so this is giving us a clue as to where we should start looking.*

One example of a material Coleman worked with that displayed interesting, emergent behavior was Cerium Copper Six Gold (CeCu6Au). CeCu6, by itself, is an ordinary nonmagnetic metal. But if you replace some of the copper atoms with gold atoms, its properties change. By adjusting the concentration of gold and the temperature, researchers can tune the material from a normal metallic state to a magnetic state as shown on this phase diagram. The boundaries

between the two phases meet at a critical point at absolute zero. At the higher temperatures accessible to experiments, there is a region between the two phase boundaries in which CeCu6Au is neither a metal nor a magnet, just as opalescent water is neither a liquid nor a gas. In this region, CeCu6Au is "quantum critical," and it is fluctuating between a magnetic phase and a metallic one. This is the kind of emergent behavior Coleman wants to understand.

> PIERS COLEMAN: *Many of us believe that if we can understand critical fluctuations then we'd maybe have a clue as to the fabric that gives rise to high temperature superconductivity. And so that, so there are these motivating ideas behind trying to understand this state of matter that separates the ordered magnet from the regular metal. And it's a very strange thing, because it only exists at one point, perhaps, in the phase diagram at low temperatures, but it effects the physics over a wide range of the phase diagram at finite temperatures.*

Coleman's colleagues, experimentalists Gabriel Applei and Almut Schroeder measured the magnetic fluctuations in CeCu6Au by running a neutron scattering experiment on the material

When neutrons come in contact with the magnetic atoms in a material, those atoms will cause the neutrons to scatter. When they scatter the neutrons lose some kinetic energy.

The energy the neutrons lose excites the magnetic fluctuations in the material.

This graph shows the results of the neutron scattering experiment with CeCu6Au. They measured the number of neutrons scattered, seen here on the y-axis, for a given amount of energy transferred to the material, the x-axis. We call this graph the spectrum of magnetic fluctuations.

Each of these different curves is showing the results of neutron scattering at different temperatures. At higher temperatures, the spectrum of the magnetic fluctuations was wide, which means they are disorganized and easy to excite. But as they lowered the temperature the spectrum of the fluctuations got narrower and narrower.

> PIERS COLEMAN: *So what do we think is going on here . . .*

When Coleman received this data he and his colleagues went to work.

> PIERS COLEMAN: *The theorist is, in the medical analogy he'd be a little like a diagnostic doctor trying to understand what the source of the disease or the infection is. You have a new discovery and you're trying to put it all together, look at all the symptoms, and with your team you actually talk about, "Well, what do you think this is? How do you think we*

> *could test that idea?" So I'm trying to collapse the data into forms that can illustrate what is actually going on.*

After a lot of analysis and collaboration with the experimentalists, colleagues and students, Coleman could see a very direct and simple relationship with the spectrum of the fluctuations and the temperature of the material.

> PIERS COLEMAN: *So one of the ideas that came out of our conversations was that one should actually look at that and plot the data as a function of the frequency, divided by the temperature. When we did that, a whole bunch of data all collapsed onto one curve. And we could write down a mathematical form for that curve. And this told us was that the characteristic time scale of the fluctuations was determined by the temperature itself.*

This discovery not only simplified the results, but it is a prime example of how, by taking an emergent viewpoint, physicists like Coleman can take something very complicated that involves billions of atoms and boil it down to a simple rule.

> PIERS COLEMAN: *What this data told us is that the old paradigm was breaking down, of metals and the nature of the metallic state and the way it transforms could not explain this data. And it tells us that something more profound and more profoundly simple is taking place at this quantum critical point. So what did it lead to? It led to recognition that we need to revise our understanding. And this led to new theories. Unfortunately at this current time, we do not have a definitive theory to explain what is different going on here.*

Coleman's work with CeCu6Au and Paul Chaikin's experiments with particles and colloids are just two small corners in the world of emergent physics, where theorists and experimentalists are trying to develop new principles that can explain the collective behavior of the many.

> PIERS COLEMAN: *What really physicists are is they're really much more like an impressionist painter or a haiku poet. And what they want to do is to condense out of the complexity the essence of the physics. And so that's our real dream is the ultimate simplification of the physics that can be captured just like a piece of haiku poetry in a simple equation.*