Krishna Rajagopal

Free the Quarks

Quantum chromodynamics, or QCD, is the theory of quarks and gluons and their interactions. Its equations are simple enough to fit on the back of an envelope. After a quick glance you might conclude that QCD is not very different from the theory of electricity and magnetism called quantum electrodynamics, or QED, which describes the behavior of electrons—for example, those in the beams within any television set or computer monitor—and the photons they interact with. The laws of QCD describe particles called quarks, which are similar to electrons except that, in addition to electric charge, they carry new charges whimsically called "colors." Their interactions involve eight new photon-like massless particles called gluons, representing eight new "color-electric" and "color-magnetic" fields. A glance at the equations of QCD suggests that they describe beams of quarks, new color forces with macroscopic range, and gluon lasers. This first impression could not be more wrong.
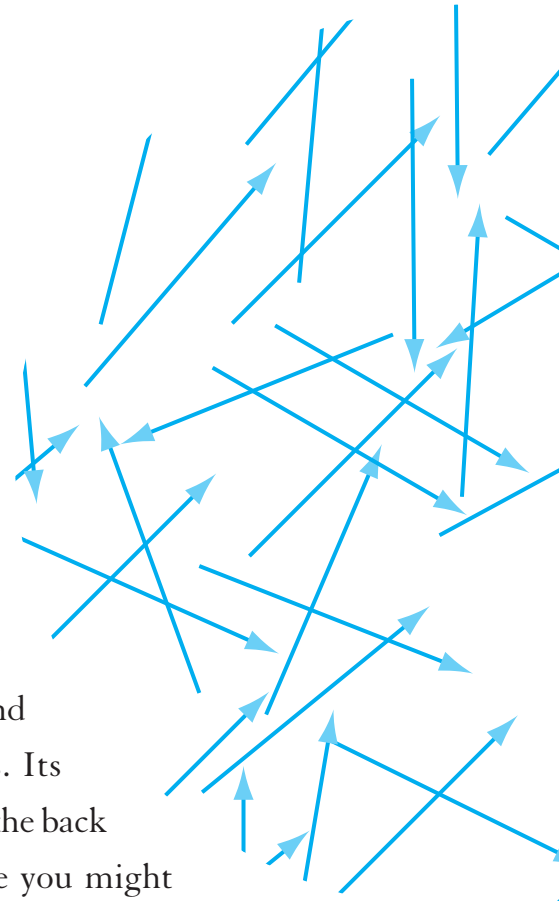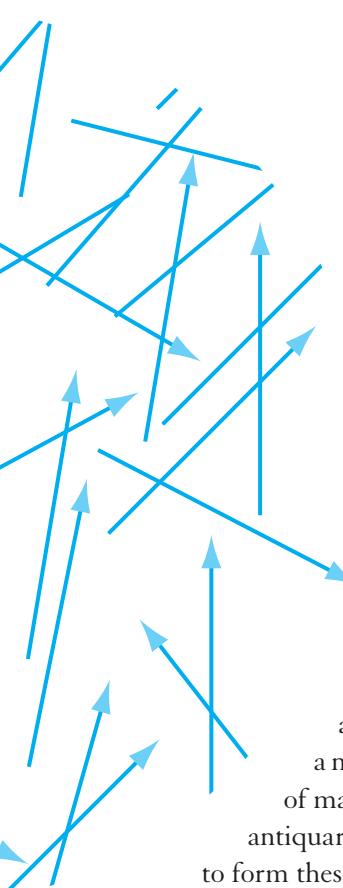
QCD describes protons, neutrons, pions, kaons, and many other subatomic particles collectively known as hadrons. A hadron has two important properties: it is "color-neutral", and it is much heavier than the quarks inside it. For example, the proton is often described as made of two up quarks and one down quark. Indeed, this combination of quarks has exactly the right electric charge (+1) and color (0) to describe a proton. But, a proton weighs about fifty times as much as these three quarks! Thus a proton (or a neutron, or any other hadron) must be a very complicated bound state of many quarks, antiquarks, and gluons (with three more quarks than antiquarks). QCD describes how the light quarks and massless gluons bind to form these complicated but colorless packages that turn out to be so heavy. It also describes how these hadrons themselves bind to form the atomic nuclei. Thus QCD describes the physics of everything that makes up our quotidian world with the exception of the electrons and photons. And yet we have never seen a beam of quarks or a gluon laser. How, then, does the reality that QCD describes turn out to be so different from what a glance at its laws seems to suggest?

The answer to this question relies on our understanding of the properties of the vacuum. Furthermore, we shall see that our naïve first impressions are actually correct at temperatures above two trillion degrees kelvin. At such ultrahigh temperatures, the stuff that QCD describes does indeed look like a plasma of free quarks and gluons. The entire Universe was at least this hot for the first ten microseconds after the Big Bang. Thus the goal of heavy-ion collision experiments is to heat up tiny portions of the Universe (located in Brookhaven, New York, and Geneva, Switzerland) to recreate these conditions, in order to study QCD by simplifying it.

IN A UNIVERSE governed by the laws of quantum mechanics, the vacuum is not empty. All states are characterized by quantum-mechanical fluctuations, and the vacuum is just the state in which these fluctuations happen to yield the lowest possible energy. In QCD, the vacuum is a frothing, seething sea of quarks, antiquarks, and gluons arranged precisely so as to have the minimum possible energy.

⦿ Six Different Quarks

To date, six different quarks have been discovered. Two quarks— named up and down—are light: only about 10 times heavier than the electron. Up quarks, down quarks, and the massless gluons are the main constituents of pions, protons, and neutrons. The proton mass is 938 MeV while the sum of the masses of two up quarks and one down quark is about 20 MeV. The strange quark is the next heaviest quark, with a mass about 20 times that of the up and down quarks. Although strange quarks do play an important role in heavy ion collisions, this article focuses on the lighter up and down quarks. The three heaviest quarks, named charm, bottom, and top, are heavy enough to be left out of this article.

Quarks	Approximate Mass(MeV/c)
up (u)	5
down (d)	10
strange (s)	150
charm (c)	1300
bottom (b)	4200
top (t)	175000

QCD describes excitations of this vacuum; indeed, we are made of these excitations. In order to understand how they turn out to be the colorless and heavy hadrons, instead of colorful and light quarks and gluons, one must better understand several striking properties of the QCD vacuum.

According to QCD, the force between quarks is actually rather weak as long as the quarks are close together, closer than 1 fermi. (One fermi, or 1 fm, equals 10^{-15} meters — or approximately the size of a proton.) This weakness of the force between nearby quarks, called "asymptotic freedom" by its discoverers David Gross, Frank Wilczek, and David Politzer, explains how we can "see" quarks at all. A microscope sufficiently powerful that it can look within a proton with a resolution much smaller than 1 fm allows one to observe weakly interacting quarks. The first sufficiently powerful microscope was the SLAC linear accelerator; quarks were first seen using this device in experiments conducted in the late 1960s by Jerome Friedman, Henry Kendall, Richard Taylor, and their collaborators.

On the Origin of Mass

The vacuum in which we live is actually filled with two condensates: a quark-antiquark condensate required by QCD and another of Higgs particles required by the weak interaction. If neither condensate were present, both quarks and protons would be massless. The quarks get their (light, but non-zero) mass from their interaction with the Higgs condensate; about 1/50th of the mass of protons and neutrons is due to its presence. The remainder of the mass of protons and neutrons (and of all hadrons) is due to the presence of the quark-antiquark condensate.

Asymptotic freedom is a property of the QCD vacuum, which describes how it responds to an "extra" quark. This quark disturbs (polarizes) the nearby vacuum, which responds by surrounding it with a cloud of many quark-antiquark pairs and gluons. In particular, this cloud acts so as to ensure that the force between this quark and another quark (surrounded by its own cloud) does not lessen as one tries to separate the quarks. Pulling a single, isolated quark completely out of a colorless hadron requires working against a force that does not weaken with increasing separation — and therefore costs infinite energy. Thus the energy of a single quark (or of any excitation of the QCD vacuum that has nonzero color) is infinite, once one includes the energy cost of the resulting disturbance of the vacuum. Adding a colorless combination of quarks to the vacuum disturbs it much less, creating a finite energy excitation. Real excitations of the QCD vacuum must therefore be colorless.

To understand why hadrons are heavy, we need a second crucial, qualitative, feature to describe the QCD vacuum. We must specify what fraction of the quark-antiquark pairs at any location is $\bar{u}u, \bar{d}d, \bar{u}d$ or $\bar{d}u$. At each point in space, the vacuum is therefore described by a "vector" that can point any direction in an abstract four-dimensional space with axes labeled $\bar{u}u, \bar{d}d$, etc. In order to achieve the lowest energy, QCD predicts that all these vectors must be aligned. A sea of quark-antiquark pairs so ordered is called a "condensate". The fact that the arrows must pick one among many otherwise equivalent directions is known as symmetry breaking. The condensate that characterizes the QCD vacuum is much like a ferromagnet, within which all the microscopic spin vectors are aligned (*Figure 1*).

If we add quarks to the QCD vacuum, they interact with this quark-antiquark condensate, and the result is that they behave as if they have a large mass. Thus the presence of a hadron disturbs the condensate, and the largest contribution to the mass of the hadron is the energy of this disturbance. In effect, the condensate slows the quarks down, and because of its presence, hadrons are much heavier than the quarks of which they are made.

There is one exception to the dictum that hadrons must be heavy. Because QCD does not specify in which direction the arrows point, it should be relatively easy to excite "waves" in which the directions of the arrows ripple as a wave passes by. In quantum mechanics, all such waves are associated with particles, and because these waves are easily excited, the related particles should not have much mass. This exception was first understood in 1961 by Yoichiro Nambu and Jeffrey Goldstone. The requisite particles, the well-known pions, weigh in at about one-seventh of the proton's mass.

Thus the QCD vacuum is a complex state of matter. The laws describing it are written in terms of colored quarks and gluons, but its natural excitations are colorless hadrons, which are heavy because of their interaction with a symmetry-breaking condensate that pervades all of space.

ONE GOOD WAY of testing our understanding of the QCD vacuum is to create new, simpler, states of matter (often called phases) in which QCD behaves as expected on first glance. Is there a phase of matter in which quarks can roam free? In which the excitations are closer to being individual quarks and gluons rather than the complicated packages we call hadrons?

Asymptotic freedom provides two ways to free the quarks. The first is to squeeze nuclei together until their protons and neutrons overlap. In the resulting "quark matter" the quarks are close together, and therefore interact only weakly. The second approach is to take a chunk of matter and heat it. When you heat a magnet, by analogy, the spins in the magnet start to oscillate; eventually, above some critical temperature, they oscillate so wildly that the spins all point in random directions, and the magnet loses its magnetization. Something similar happens in QCD. At low temperatures, the arrows that describe the QCD condensate ripple, yielding a gas of pions. Above a critical temperature, the arrows oscillate so wildly that they point randomly, and the condensate "melts". Above its critical temperature, the matter described by QCD is more disordered but more symmetric (no direction favored in *Figure 1*) than the QCD vacuum.

Theoretical calculations that strain the world's fastest supercomputers show
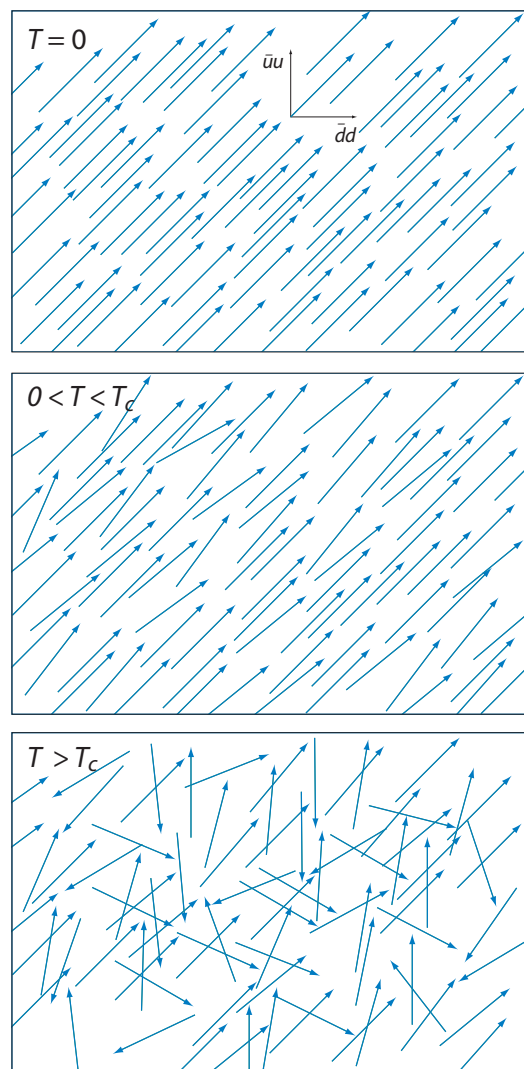
FIGURE 1

Top: *The QCD vacuum is a condensate. At each location there are quark-antiquark pairs whose type must be specified by an arrow indicating what fraction of the pairs are $\bar{u}u$ vs. $\bar{d}d$ vs. $\bar{u}d$ vs. $\bar{d}u$. Only two of these four directions are shown. The central property of a condensate is that all the arrows are aligned.*

Middle: *At non-zero temperatures, the arrows describing the condensate begin to undulate. These waves can equally well be described as a gas of particles, called pions.*

Bottom: *As the temperature increases, the waves on the condensate become more and more violent. Above some critical temperature, the arrows are completely scrambled, and the condensate has melted.*
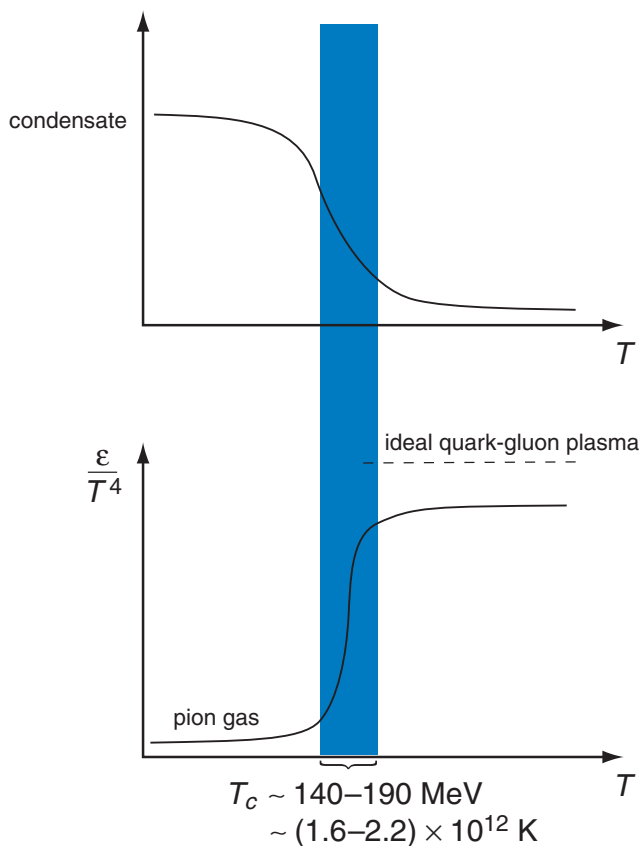
that at a temperature of about 2×10^{12} K the QCD condensate should melt and the hadrons "ionize", yielding a plasma in which the quarks are free. Once the condensate melts, hadrons need no longer be heavy, and a putative gas of them would have so many hadrons and antihadrons that these would overlap, making it impossible to tell them apart. What actually occurs (see *Figure 2*) is a phase transition to a plasma of quarks, antiquarks, and gluons. At low temperatures, QCD describes a gas of pions. Once the condensate melts, this pion gas ionizes, releasing quarks and gluons that are lighter, more numerous (three colors of each of up, down, and strange quarks plus their antiquarks and eight types of gluons) and therefore have a much larger energy density at a given temperature.

WE NOW HAVE the necessary tools to describe the prominent features on the phase diagram of QCD (*Figure 3*). At low densities and temperatures, we find the familiar world of hadrons. The only known place in which nuclei are squeezed together without being heated is the center of neutron stars. The cores of these extraordinarily dense cinders, with masses about that of the Sun but with radii of only about 10 km, may be made of superconducting quark matter.

To find a phase of matter in which QCD simplifies completely and the excitations are only quarks and gluons, we must explore the high-temperature regions of the phase diagram. Upon heating any chunk of matter to trillions of degrees, the vacuum condensate melts, the hadrons ionize, and the quarks and gluons are free to roam in the resulting quark-gluon plasma. The Universe began far up the vertical axis of the diagram: at its earliest moments, shortly after the Big Bang, it was filled with a very hot quark-gluon plasma that expanded and cooled, moving down the vertical axis, falling below 2×10^{12} K after about 10 microseconds. Since then, quarks have been confined in hadrons — with the possible exception of quarks at the centers of neutron stars and those that are briefly liberated in heavy-ion collisions.

IN A HEAVY-ION COLLISION, two nuclei accelerated to enormous energies are collided in an attempt to create a tiny, ultrahot region within which matter enters the quark-gluon plasma phase. As in the Big Bang (but much more quickly) this quark-gluon plasma droplet expands and cools, moving downward on the phase diagram. For a brief instant the quarks are free, but their liberation is short lived. After about 10^{-22} seconds they recombine to form an expanding gas of hadrons, which rattle around as they expand for perhaps another 10^{-22} seconds. After that

these hadrons are so dilute that they fly outwards without further scattering, to be seen in a detector. The STAR and PHOBOS detectors at Brookhaven National Laboratory record many thousands of hadrons - the end products of a collision in which quark-gluon plasma may have been created. (The PHOBOS detector was largely built at MIT by Profs. Busza, Roland and Wyslouch, and their collaborators, as was described in the Fall 2000 issue of *physics@mit*.)

The purpose of these heavy ion collision experiments is twofold. We hope to create a region of quark-gluon plasma - the stuff of the Big Bang — and measure its properties to see whether the complexities of the QCD vacuum have truly melted away. And, we hope to study how matter behaves as it undergoes the transition from this plasma back to a mundane hadron gas.

For the last five years, the highest-energy heavy-ion collisions occurred in experiments done at the Super Proton Synchrotron (SPS) at CERN. But in June 2000, the first collisions occurred at Brookhaven's new Relativistic Heavy Ion Collider (RHIC) whose collisions are about 10 times more energetic. What does this big energy increase buy? It boosts the initial energy density, and thus the initial temperature, pushing further upward into the expected quark-gluon plasma region of the phase diagram. In addition, these higher energy collisions produce many more pions, diluting the net quark density. As we build more energetic heavy-ion colliders, therefore, we explore upwards and to the left on the phase diagram, more closely recreating the conditions of the Big Bang. To date, we have only the first, simplest analyses of collisions at RHIC, but it is already clear that these collisions have higher initial energy densities and lower net quark densities than at the SPS.

The intriguing SPS results reveal several aspects that are difficult to model using only the physics of hadrons. One example is the paucity of J/ψ particles, which include one charm and one anticharm quark. As charm quarks are heavy, they are produced only rarely in a heavy-ion collision. Those few that do occur arise from the earliest most energetic quark-quark collisions. If a charm and anticharm quark are created in a quark-gluon plasma (wherein they are free to wander), they are unlikely to find each other and form a J/ψ. The striking paucity of J/ψ particles in measurements by the NA50 experiment at the SPS is therefore quite interesting. Further experiments by NA50 and the PHENIX experiment at RHIC should help to resolve remaining ambiguities in the interpretation of these data. One interpretation is that the SPS heavy-ion collisions are exploring the crossover region in the phase diagram (the blue-shaded "in-between region" of *Figure 2*), where
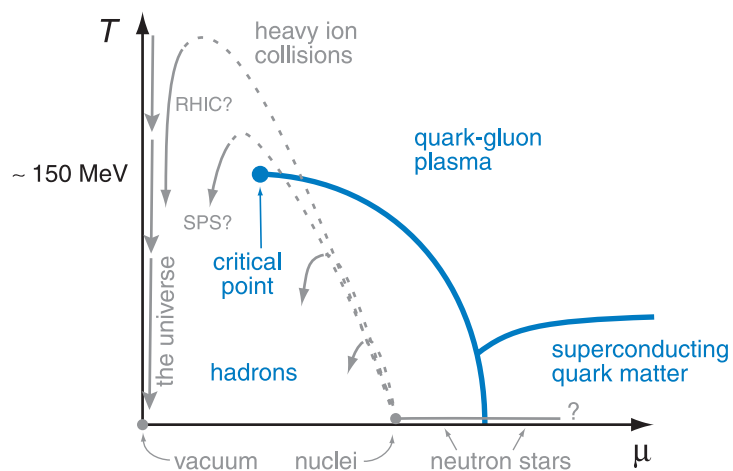

FIGURE 3

Phases of QCD as a function of temperature and μ*, a quantity that is a convenient measure of the net quark density, namely the density of quarks minus that of antiquarks. The vacuum is at the bottom left; nuclei have non-zero net quark density. Squeezing nuclei without heating them pushes matter to the right on the diagram, while heating matter pushes it up. The blue line separating the quark-gluon plasma from the hadronic phase ends at a critical point.*

QCD is not well described either as a gas of hadrons or as a quark-gluon plasma. How can we test this hypothesis?

One idea uses the fact that higher energy collisions cool by passing through the phase transition region farther to the left. Near the vertical axis of the phase diagram (traversed by the Big Bang and by the highest energy collisions), the phase transition from quarks to hadrons occurs smoothly and continuously. It is therefore quite different from the boiling of water, which occurs at a sharply defined temperature at which its properties change sharply. Theoretical arguments suggest that at higher net quark density, the phase transition between quark-gluon plasma and hadrons is similarly discontinuous and can be shown in *Figure 3* as a sharp line. This line ends at what is called the "critical point".

There are phenomena that occur at the critical point and nowhere else on the phase diagram. At this point, the arrows of *Figure 2* undulate in a unique, precisely calculable, manner. Consequently, distinctive fluctuations occur in those heavy-ion collisions that pass near the critical point as they cool. For example, the mean momentum of the 100 lowest-energy pions in a collision should vary enormously from one collision to the next. The NA49 experiment at the SPS has done a careful search for such fluctuations but has not seen any. The search for the critical point continues, with RHIC exploring to the left in *Figure 3* and new lower energy SPS collisions exploring further to the right. Early indications are that fluctuations in RHIC collisions are an order of magnitude larger than those at the SPS, but it remains to be determined whether these have the characteristic features that would signal the discovery of the critical point.

In addition to studying the transition between quark-gluon plasma and hadrons, we wish to use heavy-ion collisions to measure properties of the newly created quark-gluon plasma itself. To do so, we need observables that tell us about the earliest, hottest, moments of a collision. One simple way is to shoot a very fast quark through the plasma and watch how rapidly it loses energy. Estimates suggest that a quark plowing through such a plasma loses much more energy than it would if it encounters only heavy, colorless hadrons. We search for signs of this rapid energy loss by looking for a paucity of 5-10 GeV pions emerging from a heavy ion collision. Any such energetic pions must have originated as a fast quark. If these quarks have to fight their way through a quark-gluon plasma, they will lose energy and thermalize, and consequently very few 5-10 GeV pions will be seen, relative to what occurs in proton collisions.

Despite best efforts, however, no evidence of such a deficit has been seen at the SPS. Perhaps the most exciting announcement at the recent Quark Matter conference was that preliminary data from both the STAR and PHENIX experiments show about 5 times fewer energetic pions than expected. With time, this observation should become a quantitative measure that will allow us to test whether high temperature QCD indeed describes a quark-gluon plasma — and to test predictions of its properties.

We wait with great interest, hoping that experimenters soon confirm they are

regularly recreating the very stuff of the Big Bang. As they then begin to measure its properties, we shall learn whether QCD behaves as expected. If the vacuum condensate melts and hadrons ionize, freeing the quarks, we shall have realized the dream of simplicity implicit in the laws of QCD.

Acknowledgements

KRISHNA RAJAGOPAL *is an Associate Professor of Physics in the MIT Center for Theoretical Physics. He enjoys thinking about QCD in extreme conditions because it requires linking usually disparate strands of theoretical physics, from particle and nuclear physics to cosmology, astrophysics and condensed matter physics. His recent research interests include the physics of the critical point in the QCD phase diagram, described in this article, and the properties of the cold, dense quark matter that may lie at the centers of neutron stars. His recent work shows that a lump of cold quark matter behaves like a transparent insulator, and not like an electric conductor as previously assumed. Rajagopal is a Department of Energy Outstanding Junior Investigator and an Alfred P. Sloan Research Fellow. He has been awarded the Physics Department Buechner Teaching Prize.*