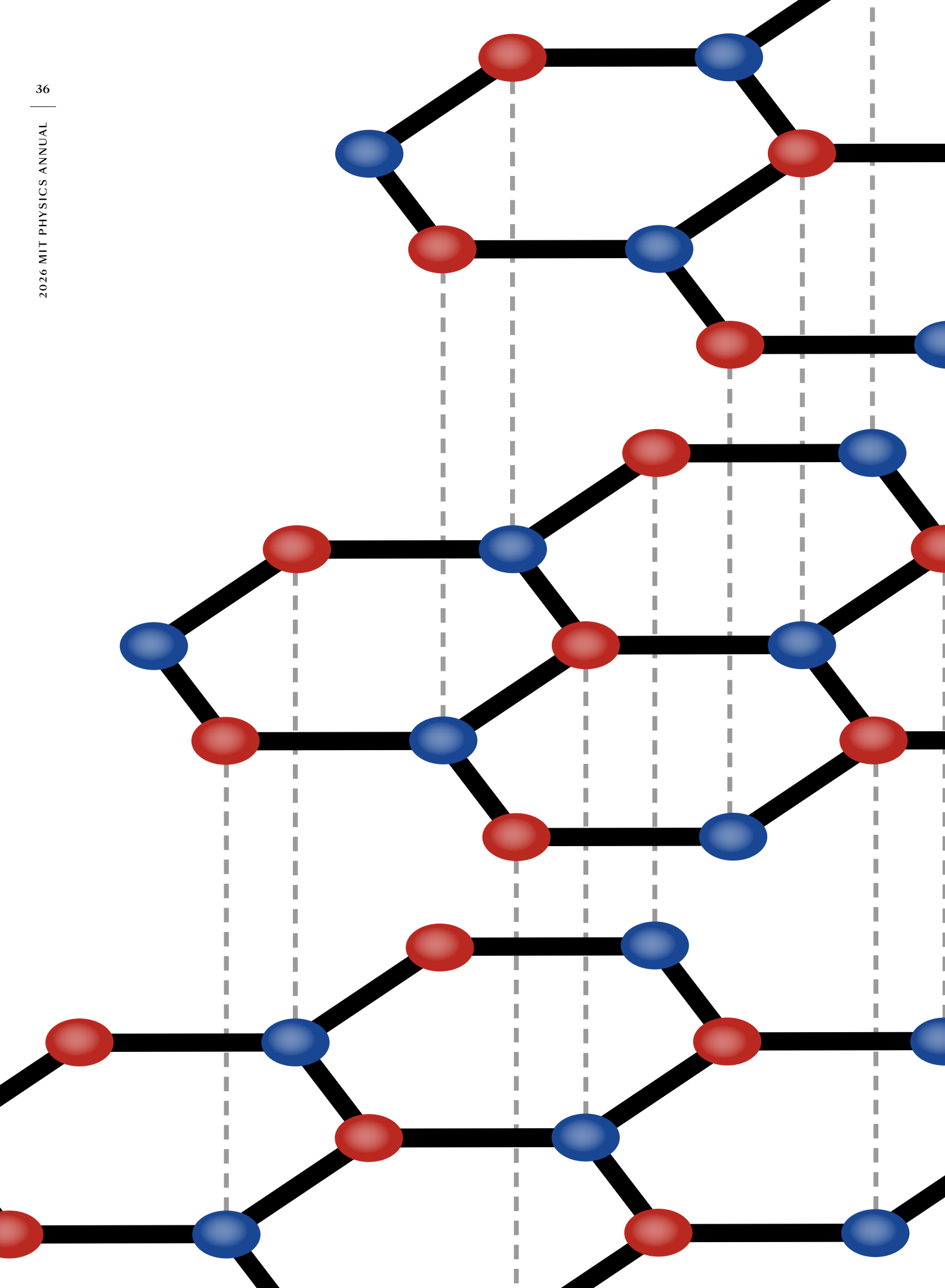
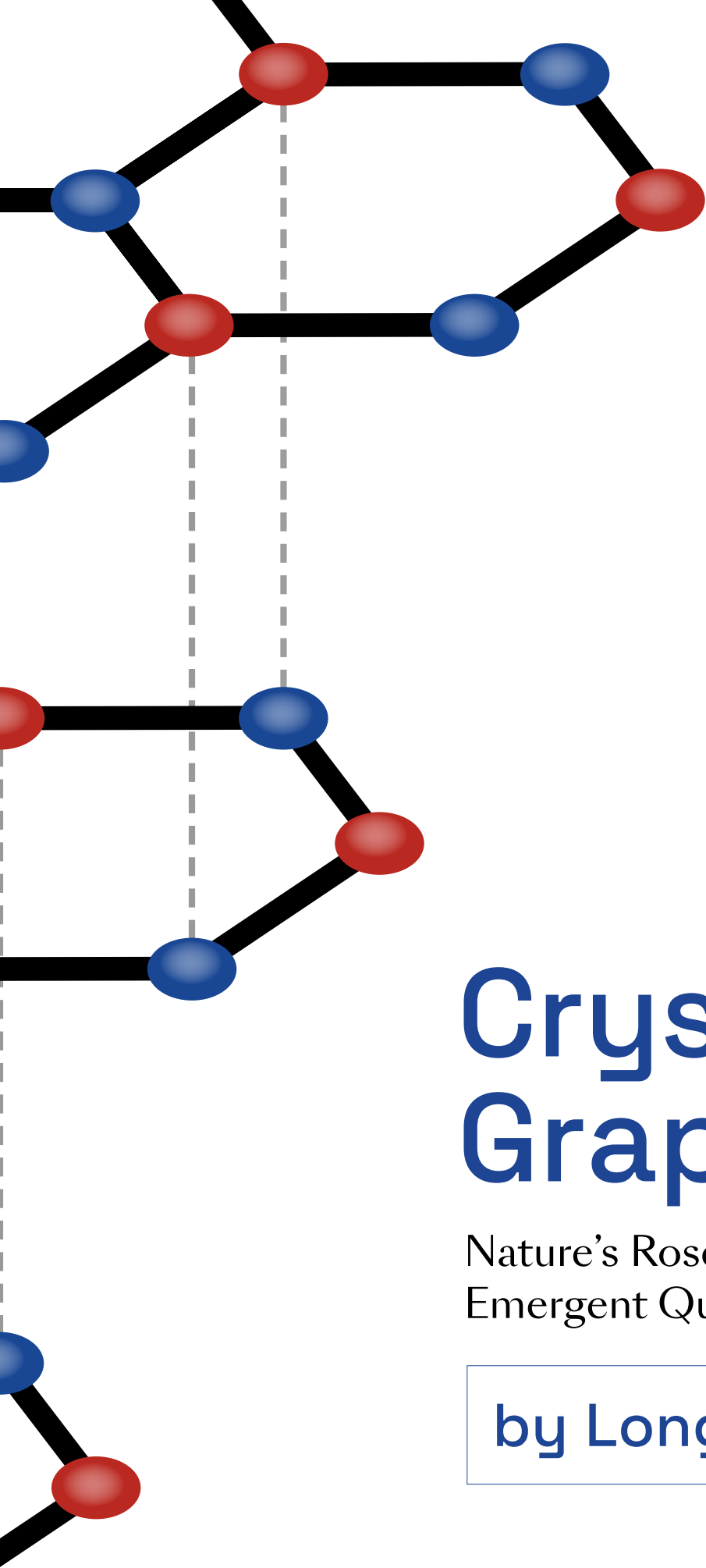






Crystalline Graphene:

Nature's Rosetta Stone of
Emergent Quantum Phenomena

by Long Ju

More is different—the philosophy of constructionism

If someone asked the question “What is MIT?”, most people would agree that the answer should be composed of two key parts: who is at MIT and how do they interact with each other. The individuals define the basic building blocks, while their interactions more often determine the structure and how the community exhibits itself to outside observers. These simple empirical rules apply to any community like MIT, or a state or a nation, and they guide our exploration and understanding of nature as well.

For a long time in scientific history, physicists tried to understand the composition of the material universe by seeking the smallest units of matter. This approach of reducing matter, named as *reductionism* in philosophy, can be traced back to ancient Greece when the word *atom* was coined. The associated natural philosophy, Atomism, proposed that the physical universe is composed of fundamental indivisible components known as atoms. Following this reductionism philosophy,

FIGURE 1:
(a) Electron pairs lead to zero resistance and perfect exclusion of the magnetic field in superconductors.
(b) Illustration of the fractional quantum Hall effect, in which interacting electrons effectively break into fractions.
Credit: Ju Group, MIT.

the building blocks is enough to understand matter and nature. There are simple examples to justify this question: both graphite and diamond are composed of the same simple carbon atoms, but they exhibit contrasting properties in almost every sense—soft vs. hard, opaque vs. transparent, conducting vs. insulating. How the

particle physicists have discovered many elementary particles and the Standard Model, which greatly improved our understanding of the universe.

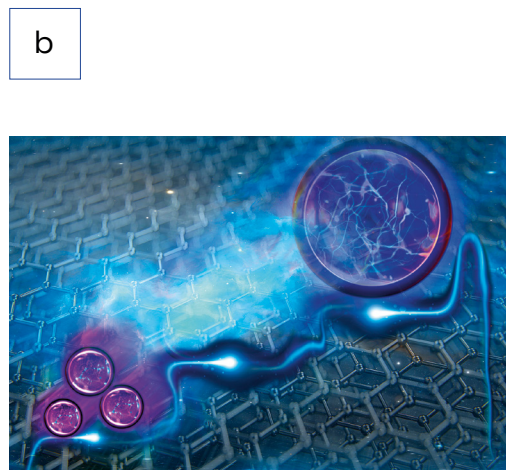
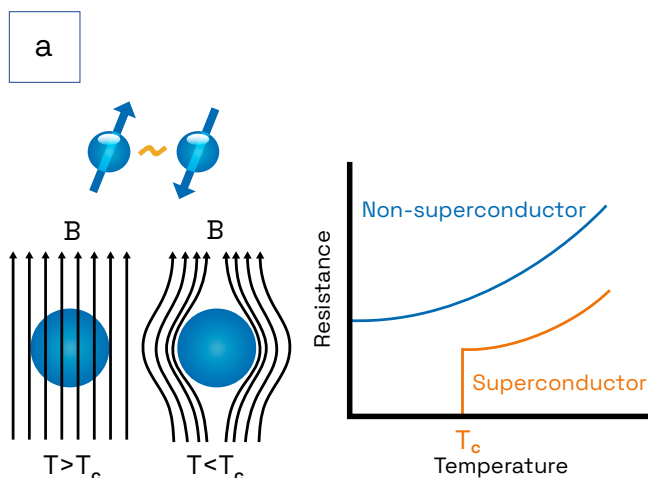
On the other hand, physicists asked if knowing

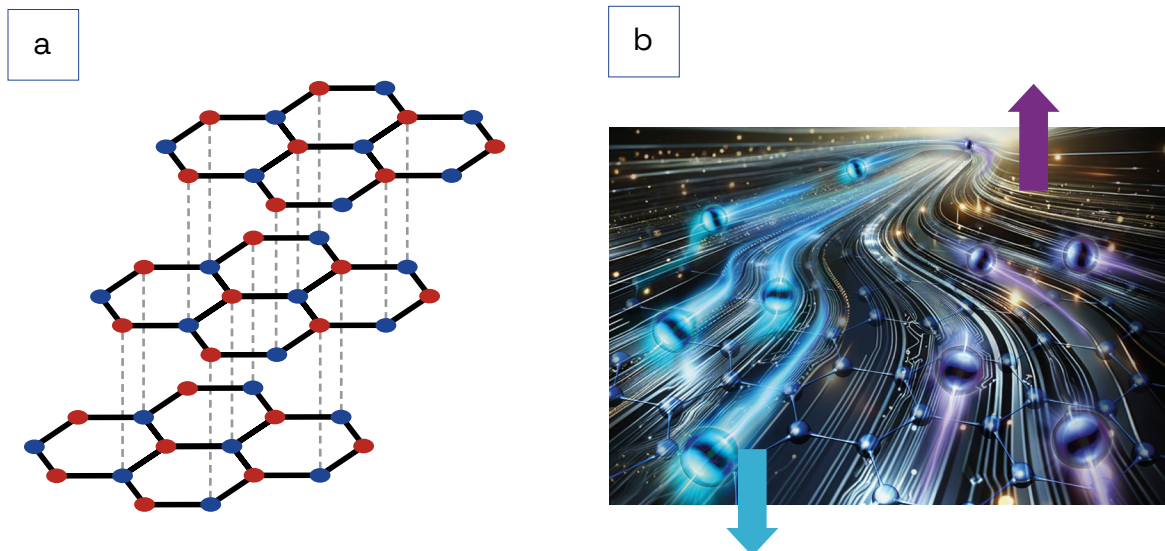
building blocks are arranged into crystal structures and interact with each other can lead to dramatically different macroscopic phenomena. This idea is described as the philosophy of *constructionism*, in contrast to reductionism, and it tells us that new and unexpected properties could emerge from the assembly of simple elementary particles.

This philosophy is best explained by Philip Anderson in “More is Different.” [1] The early development of the quantum theory of solid-state materials, later coined by Anderson as condensed matter physics, has led to the successful categorizations of metals, semiconductors, and insulators. Some of these materials form the foundation of the electronic and optical industries, which have completely transformed our society. Condensed matter physicists aim to explore and understand such emergent phenomena in various solid-state materials. These materials provide an extremely rich platform to explore emergent quantum phenomena, given their rich chemical compositions and structures.

Electron correlation and topology: pillars of modern condensed matter physics

While condensed matter materials are composed of atoms, which include nuclei and electrons, most of their properties are determined by the behavior of electrons. In the simplest picture to describe electrons in crystals, they are treated as independent particles. This single-particle assumption has proven to be very effective in predicting the basic properties of many metals, semiconductors, and insulators. However, electrons interact with each other through the Coulomb repulsion and Fermi-Dirac statistics rules. When such interactions are strong enough and electrons’ behaviors are strongly correlated, completely new phenomena can emerge from the large collection of electrons: a form of constructionism that is specific to electrons,





which is one of the most well-understood of elementary particles. These phenomena are the central topics of modern condensed matter physics, and their underlying principles are much more awe-inspiring than the simple principles that distinguish metals from insulators.

Two famous examples best represent these two principles. In 1911, the first superconductor was discovered when mercury was cooled down to about -269° Celsius. The microscopic understanding was not available until four decades later, which suggests that, remarkably, electrons attract each other and form pairs in superconductors. The properties of superconductors are effectively determined by these pairs, as if the pairs are the elementary particles instead of the constituent electrons! Since then, many superconductors, including some at much higher temperatures, have been discovered. Phenomenologically, superconductors appear as just perfect metals that have zero electrical resistance, but soon they were found to be a completely new phase of interacting electrons that also perfectly expels magnetic field. This field expulsion, known as the Meissner Effect, is observed widely in superconductors, regardless of the specific superconducting material.

In another case, the electrical resistance of certain materials is measured to be perfectly quantized. In early 1980s, physicists measured some very clean materials based on silicon and gallium arsenide, in which electrons are confined in a quasi-two-dimensional plane. When subjected to a high magnetic field, the so-called Hall resistance was shown to be exactly the same value as defined by $h/\nu e^2$, where h and e are fundamental constants in physics, and ν is either an integer [2] or fraction [3]. These phenomena, known as *integer and*

FIGURE 2: (a) Layers of carbon forming the rhombohedral stacking order, as part of natural graphite. Credit: Ju Group, MIT. (b) Illustration of IQAHE, which spatially separates traffic of forward- and backward-moving electrons to avoid colliding. Credit: Sampson Wilcox, MIT RLE and Ju Group, MIT.

fractional quantum Hall effect, revealed for the first time perfect quantization of a physical quantity in condensed matter materials. The implication is deep and profound: if real materials have defects and disorders and are far from perfect, why would the collection of electrons decide to exhibit perfectly quantized resistance that is accurate down to nine zeros after the decimal point? It was later found that the underlying principle is rooted in topology of the electronic band structure, much like the difference between a donut and an orange: the former has one hole, while the latter has zero, so they each have a distinct topology, unless a violent operation transforms one to another.

The Rosetta stone of emergent quantum phenomena?

Apart from the examples given above, condensed matter materials have exhibited various emergent quantum phenomena driven by electron correlation and topology, sometimes with the two mechanisms intertwined. Given that there are more than 100 elements in the periodic table, and one can combine pretty much an arbitrary number of them to assemble into crystals, the power of constructionism to enable a plethora of emergent phenomena seems to be well-justified and expected.

However, instead of synthesizing many complex materials, our group at MIT focuses on a particularly simple material that is a few layers of carbon atoms, known as *rhombohedral graphene (RG)*. We start with

ordinary graphite, which is pencil lead, that can be exfoliated into thin layers by peeling with ordinary tape. Within the exfoliated thin layers, we find that regions of RG exist. Although extremely simple in its chemical composition and structure, by early 2023 RG has already exhibited very interesting properties that are both within and beyond the single-particle picture. Thanks to the collective efforts by several groups in the U.S. and U.K., we already knew that RG can be a metal, semiconductor, insulator, and even a superconductor, depending on the experimental conditions. In particular, we at MIT observed a so-called *integer quantum anomalous Hall effect (IQAHE)*, which effectively demonstrated an electronic highway along which electrons propagate without energy dissipation [4].

Given these initial rich observations, we wondered if RG could be a model system to explore, engineer, and understand various emergent quantum phenomena in condensed matter physics? In the history of

FIGURE 3:
(a) Moiré superlattice formed between graphene and hBN as a spatial beating pattern. (b) FQAHE with plateaus of the Hall resistance (R_{xy}) precisely quantized at $h/\nu e^2$, where ν takes fractional values. Credit: Guorui Chen/Shanghai Jiao-Tong University.

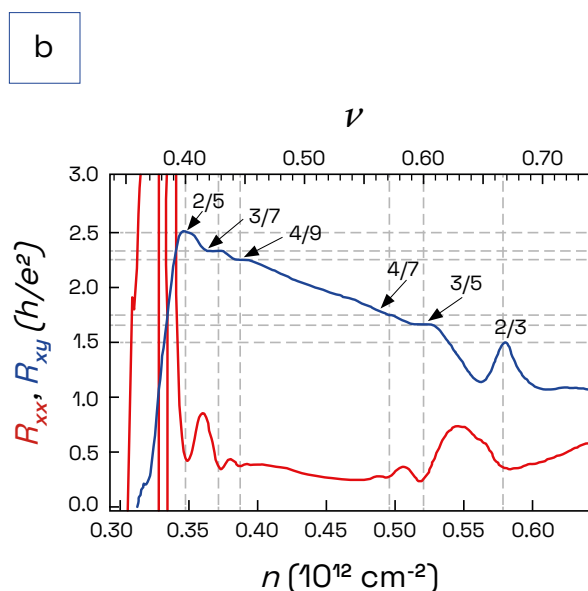
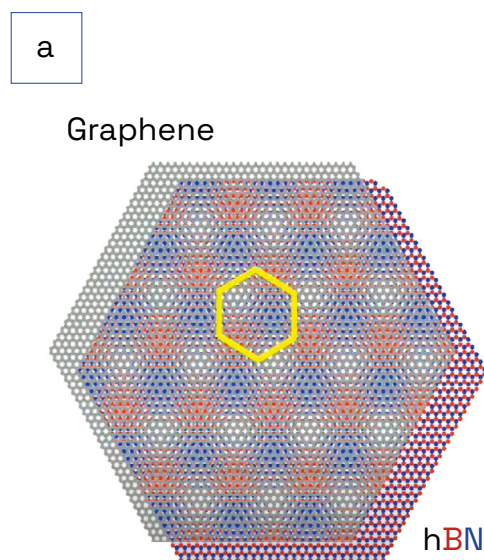
deciphering ancient Egyptian literatures, the Rosetta Stone played the key role, as it provides a dictionary for translation. Given the vast variety of condensed matter materials with different chemistry and structures, and the wide range of emergent phenomena, can we use RG as the Rosetta Stone to understand existing phenomena, for which theories are still being

developed? And even better, can we use it as the crystal ball to predict unprecedented phenomena, which are beyond theoretical expectations?

Unprecedented and unpredicted duo

The real excitement in RG for emergence started in the summer of 2023, when we observed the fractional quantum anomalous Hall effect (FQAHE) [5]; “anomalous” means at zero magnetic field. It shows the same perfectly quantized Hall resistance as the Nobel Prize-winning fractional quantum Hall effect, but this time at zero magnetic field. Our device contains a five-layer RG flake and another flake material called hexagonal boron nitride (also known as “white graphene”). They form a moiré superlattice, kind of a spatial beating between two atomic patterns that have slightly different periods. Our observed FQAHE was made in the absence of any theoretical predictions, and happened shortly after a similar effect was reported the same summer in a very different material of twisted MoTe2. FQAHE was predicted for twisted MoTe2, but the same theory does not seem to work for graphene. Even after three years of heavy investigations by theorists all around the world the underlying mechanism is still under debate and remains a central problem in the field.

To understand the mechanism of FQAHE in graphene, we further explored a device in which RG and hBN form a very large twist angle, which was known to suppress or eliminate the moiré effect. This time there is no FQAHE, but instead superconductivity [6].



Surprisingly, this superconductor exhibits some very exotic phenomena not observed in any other superconductors since 1911: when the external magnetic field is swept, the resistance of the superconductor goes from zero to finite to zero and shows a delay

FIGURE 4:
(a) Structurally chiral molecules that form mirror images. (b) and (c) Chiral superconductor with electron pairs winding clockwise and counter-clockwise (forming mirror images), resulting in opposite angular and magnetic moment states that are connected by hysteretic resistance curve under scanning magnetic field. Credit: Ju Group, MIT.

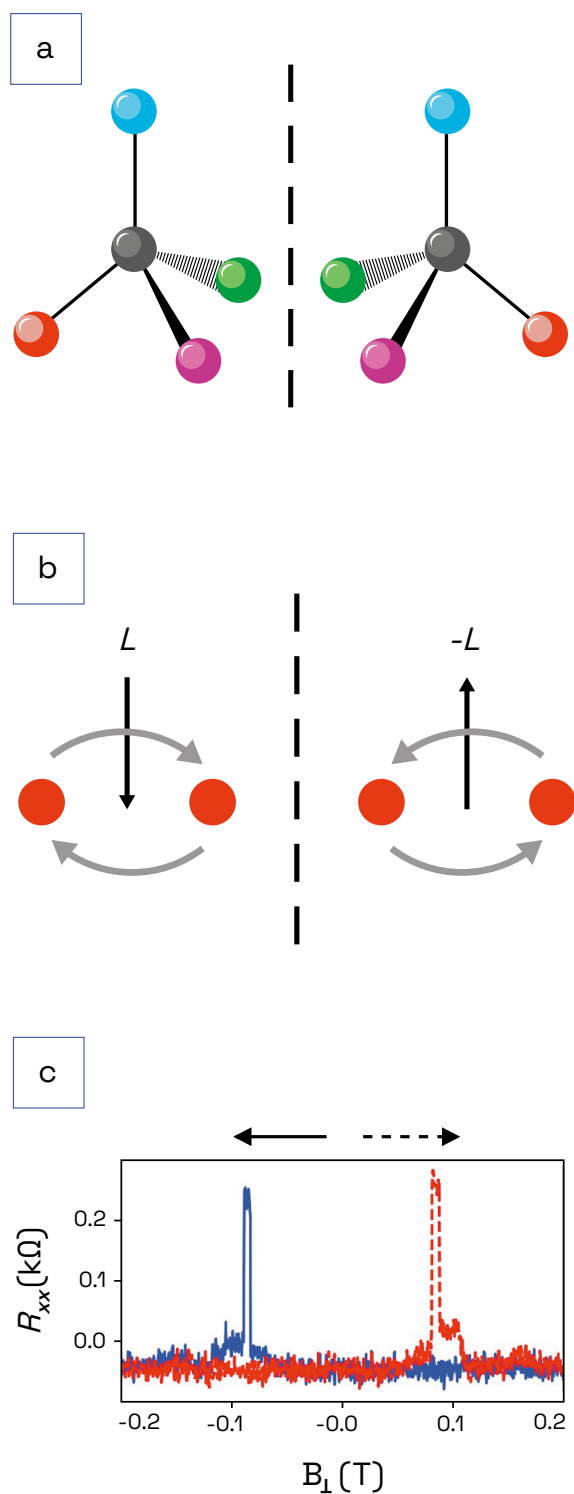
between forward and backward scanning. Such kind of magnetic field dependence, known as *hysteresis*, indicates that the superconductor is itself a magnet! This directly challenges the conventional understanding that superconductivity and magnetism are mutually exclusive. A direct

consequence is that the superconductor spontaneously picks up chirality, which usually describes the left- and right-hand-like structures in chemical molecules. Here the pairs of electrons do not harbor structural chirality, instead they circle around clockwise or counter-clockwise, corresponding to left- or right-handedness.

Both the FQAHE and chiral superconductivity are unique quantum states of interacting electrons, and neither of them was predicted in RG by theory before our experiments. They both exhibit new features that distinguish from the conventional quantum Hall materials and superconductors. The most surprising thing is that the duo of these unprecedented and unpredicted emergent quantum phenomena co-exist in simple crystalline graphene, which is the gift by nature.

A new paradigm of quantum many-body physics

One might ask how can a single material exhibit so many different properties? The truth is that we are not just dealing with what nature invented; we can control the properties of RG by tuning a range of experimental knobs. For example, we can apply electric voltages through the so-called gates near the two-dimensional RG flake. This allows us to add or withdraw electrons from RG and change the energy of states, independently. In addition, we can proximitize RG by other materials such as hBN and semiconductors, to endow new flavors to electrons in RG, such as the so-called spin-orbit coupling, which is usually very weak in carbon atoms, and the moiré superlattice effect, which modulates the electric potential in addition to that from the carbon



atom itself. Through these operations, we can transform RG into effectively a million different conventional materials, each of which has its own interesting properties. We note that the most important factor underscoring the majority of the observed phenomena is the so-called flat electronic band. Electrons in this condition behave as though they are very heavy and move slowly so that they have enough time to interact

with each other and co-ordinate behaviors in a strongly correlated way. This is much like two persons sitting down to chat to make a plan in a relaxed environment, instead of rushing past each other quickly.

We tune all the experimental knobs and study RG in our lab at MIT, practicing a new paradigm of condensed matter physics. Compared to synthesizing materials with complex chemistry and structure, this new and controlled paradigm allows us to separate the effects of different factors and identify the key one that is responsible for an observed phenomenon. It demonstrates a deep and intriguing unification of the reductionism and constructionism: the simplest components can be tuned to interact strongly and generate the most complex phenomena—a new philosophical way of understanding condensed matter physics and nature.

Into the future

This new paradigm opens up exciting opportunities for further exploring quantum emergence and constructionism. For example, the FQAHE state is expected to host the so-called anyons—entities that have fractional charge and obey fractional statistics rules that are different from fermions or bosons. Anyons are not real particles, as they only emerge as a consequence of interactions between electrons. However, they exhibit measurable experimental effects which are the same as if they are real particles.

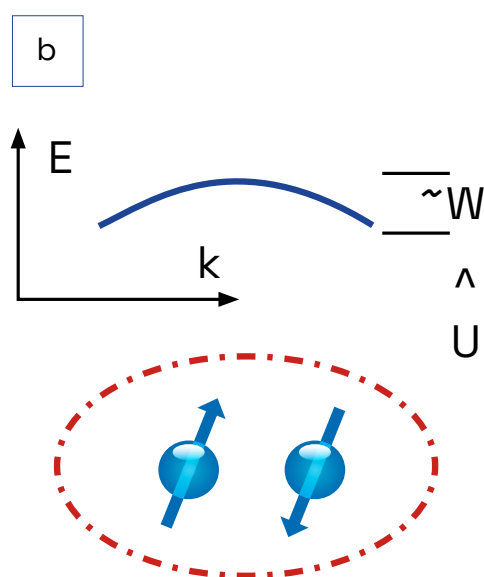
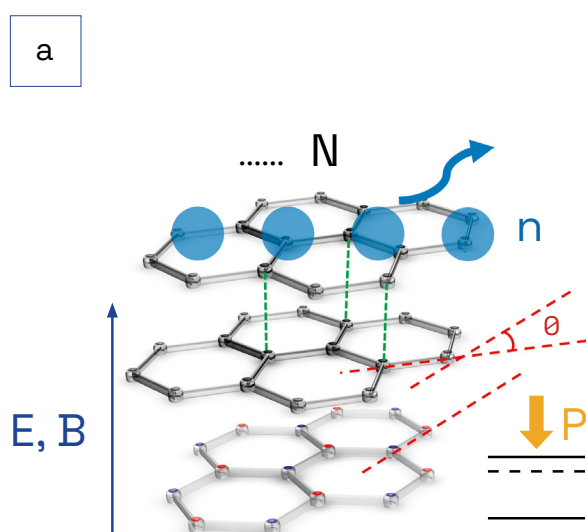
On the other hand, chiral superconductivity is expected to host Majorana zero modes—a quasiparticle that is its own anti-particle and with memory of the history of being exchanged with other Majorana particles. This is different from fermions and bosons, the two categories that all real particles belong to, for which exchanging two particles merely results in an additional phase factor of wave function. The memory effect of exchanging Majorana zero modes can be utilized to engineer quantum bits, which could resist perturbations from the environment and improve the performance of quantum computers.

Regardless of applications, our observations point to exploring constructionism at a fresh new level: given the various states of crystalline graphene, which already host intriguing emergent phenomena, one can envision

constructing completely new devices to place these phenomena at close proximity and exploring what could emerge from their interactions. What to expect? Only time can answer it. Right now, we are collaborating with several condensed matter

physics groups at MIT to explore this frontier—those of Professors Ray Ashoori, Liang Fu, Senthil Todadri, and Xiao-Gang Wen.

FIGURE 5:
(a) Multiple knobs to enrich RG: layer number N , twist angle θ , electric field E , magnetic field B , electron density n and pressure P .
(b) Flat band promotes electron correlation effect when the kinetic energy W is dwarfed by the interaction energy U . Credit: Ju Group, MIT.



LONG JU is the Lawrence C. (1944) and Sarah W. Biedenharn Associate Professor of Physics at MIT. His research group focuses on understanding light-matter interactions and electron transport in novel quantum materials. Of particular interest are atomically thin materials and their van der Waals hetero-structures. These materials host a variety of fascinating electronic and optical properties individually, and they offer exciting opportunities to explore possibilities enabled by controlling the stacking order and electrically tuning the band structure and charge doping. Especially, such materials provide a new platform to design and engineer more exotic quantum phenomena when electron correlations and topology are included. The Ju Group develops problem-oriented experiments by employing various optical spectroscopy and microscopy tools in a broad spectrum range from UV to THz, as well as DC transport measurements. Ultrafast optical techniques and scanning probe optical microscopy will be utilized to study dynamical properties on a time scale down to femtoseconds and a spatial resolution of nanometers. Most importantly, device fabrication and application of electric and magnetic fields will be combined to achieve external control of material properties.

Long Ju joined the MIT Physics Department as an assistant professor in January 2019. He received his BS in Physics in 2009 from Tsinghua University, China, and his PhD in Physics in 2015 from the University of California, Berkeley. He then moved to Cornell University, where he was a Kavli postdoctoral fellow until December 2018. Long Ju's honors and awards include a Sloan Research Fellowship, the OCPA Outstanding Young Researcher Award (Macronix Prize), and *MIT Technology Review's* Innovators Under 35.

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