Foreword

In 1989 I attended a workshop at the University of Minnesota. The organizers had hoped the workshop would spawn new ideas about the origin of high-temperature superconductivity, which had recently been discovered. But I was especially impressed by a talk about the fractional quantum Hall effect by a young physicist named Xiao-Gang Wen.

From Wen I heard for the first time about a concept called *topological order*. He explained that for some quantum phases of two-dimensional matter the ground state becomes degenerate when the system resides on a surface of nontrivial topology such as a torus, and that the degree of degeneracy provides a useful signature for distinguishing different phases. I was fascinated.

Up until then, studies of phases of matter and the transitions between them usually built on principles annunciated decades earlier by Lev Landau. Landau had emphasized the crucial role of symmetry, and of local order parameters that distinguish different symmetry realizations. Though much of what Wen said went over my head, I did manage to glean that he was proposing a way to distinguish quantum phases founded on much different principles that Landau's. As a particle physicist I deeply appreciated the power of Landau theory, but I was also keenly aware that the interface of topology and physics had already yielded many novel and fruitful insights.

Mulling over these ideas on the plane ride home, I scribbled a few lines of verse:

> *Now we are allowed*
> *To disavow Landau.*
> *Wow ...*

Without knowing where it might lead, one could sense the opening of a new chapter.

At around that same time, another new research direction was beginning to gather steam, the study of *quantum information*. Richard Feynman and Yuri Manin had suggested that a computer processing quantum information might perform tasks beyond the reach of ordinary digital computers. David Deutsch formalized the idea, which attracted the attention of computer scientists, and eventually led to Peter Shor's discovery that a quantum computer can factor large numbers in polynomial time. Meanwhile, Alexander Holevo, Charles Bennett and others seized the opportunity to unify Claude Shannon's information theory with quantum physics, erecting new schemes for quantifying quantum entanglement and characterizing processes in which quantum information is acquired, transmitted, and processed.

The discovery of Shor's algorithm caused a burst of excitement and activity, but quantum information science remained outside the mainstream of physics, and few scientists at that time glimpsed the rich connections between quantum information and the study of quantum matter. One notable exception was Alexei Kitaev, who had two remarkable insights in the 1990s. He pointed out that finding the ground state energy of a quantum system defined by a local Hamiltonian, when suitably formalized, is as hard as any problem whose solution can be verified with a quantum computer. This idea launched the study of *Hamiltonian complexity*. Kitaev also discerned the relationship between Wen's concept of topological order and the *quantum error-correcting codes* that can protect delicate quantum superpositions from the ravages of environmental decoherence. Kitaev's notion of a *topological quantum computer*, a mere theorist's fantasy when proposed in 1997, is by now pursued in experimental laboratories around the world (though the technology still has far to go before truly scalable quantum computers will be capable of addressing hard problems).

Thereafter progress accelerated, led by a burgeoning community of scientists working at the interface of quantum information and quantum matter. Guifre Vidal realized that many-particle quantum systems that are only slightly entangled can be succinctly described using *tensor networks*. This new method extended the reach of mean-field theory and provided an illuminating new perspective on the successes of the *Density Matrix Renormalization Group (DMRG)*. By proving that the ground state of a local Hamiltonian with an energy gap has limited entanglement (the *area law*), Matthew Hastings showed that tensor network tools are widely applicable. These tools eventually led to a complete understanding of gapped quantum phases in one spatial dimension.

The experimental discovery of *topological insulators* focused attention on the interplay of symmetry and topology. The more general notion of a *symmetry-protected topological (SPT) phase* arose, in which a quantum system has an energy gap in the bulk but supports gapless excitations confined to its boundary which are protected by specified symmetries. (For topological insulators the symmetries are particle-number conservation and time-reversal invariance.) Again, tensor network methods proved to be well suited for establishing a complete classification of one-dimensional SPT phases, and guided progress toward understanding higher dimensions, though many open questions remain.

We now have a much deeper understanding of topological order than when I first heard about it from Wen nearly 30 years ago. A central new insight is that topologically ordered systems have *long-range entanglement*, and that the entanglement has universal properties, like *topological entanglement entropy*, which are insensitive to the microscopic details of the Hamiltonian. Indeed, topological order is an intrinsic property of a quantum state and can be identified without reference to any particular Hamiltonian at all. To understand the meaning of long-range entanglement, imagine a quantum computer which applies a sequence of geometrically local operations to an input quantum state, producing an output product state which is completely disentangled. If the time required to complete this disentangling computation is independent of the size of the system, then we say the input state is *short-ranged entangled*; otherwise it is *long-range entangled*. More generally (loosely speaking), two states are in different quantum phases if no constant-time quantum computation can convert one state to the other. This fundamental connection between quantum computation and quantum order has many ramifications which are explored in this book.

When is the right time for a book that summarizes the status of an ongoing research area? It's a subtle question. The subject should be sufficiently mature that enduring concepts and results can be identified and clearly explained. If the pace of progress is sufficiently rapid, and the topics emphasized are not well chosen, then an ill-timed book might become obsolete quickly. On the other hand, the subject ought not to be *too* mature; only if there are many exciting open questions to attack will the book be likely to attract a sizable audience eager to master the material.

I feel confident that *Quantum Information Meets Quantum Matter* is appearing at an opportune time, and that the authors have made wise choices about what to include. They are world-class experts, and are themselves responsible for many of the scientific advances explained here. The student or senior scientist who studies this book closely will be well grounded in the tools and ideas at the forefront of current research at the confluence of quantum information science and quantum condensed matter physics.

Indeed, I expect that in the years ahead a steadily expanding community of scientists, including computer scientists, chemists, and high-energy physicists, will want to be well acquainted with the ideas at the heart of *Quantum Information Meets Quantum Matter*. In particular, growing evidence suggests that the quantum physics of spacetime itself is an emergent manifestation of long-range quantum entanglement in an underlying more fundamental quantum theory. More broadly, as quantum technology grows ever more sophisticated, I believe that the theoretical and experimental study of highly complex many-particle systems will be an increasingly central theme of 21st century physical science. It that's true, *Quantum Information Meets Quantum Matter* is bound to hold an honored place on the bookshelves of many scientists for years to come.

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