Preface

Understanding the basic structure of matter and measuring this structure in detail have long presented a challenge to philosophers and scientists. In the fifth century B.C., the Greek philosopher Democritus described the ultimate structure of matter as discrete rather than continuous and is reported to have said that "The only existing things are atoms and empty space; all else is mere opinion." This atomistic theory became a cornerstone of the philosophy of Epicurus and was described much later by Lucretius in his didactic poem *De Rerum Natura*. According to this philosophy, the properties of material objects were considered to be determined solely by the sizes, shapes, positions, and motions of the atoms of which the material was constituted.

The same philosophy appears in the writings of Newton, Descartes, and others in the 17th century. In fact, it was not until the 18th century that a more scientific, as contrasted with philosophical, view of atoms was taken. Probably the first step in this direction was the work of D. Bernoulli, who in 1738 demonstrated that the pressure dependence of a confined gas on its volume could be developed from an atomic model. Subsequently, the key papers of J. Dalton in 1808 and A. Avogadro in 1811 established that certain hypotheses based on atomic theory furnished a firm basis for the understanding of a number of important chemical observations. In fact, this work marked the beginning of the modern science of chemistry. Although it took many years for these ideas to be fully accepted, by the end of the 19th century rough determinations of both the size and mass of various atoms had been made.

However, the evidence on the existence of atoms continued to be indirect. The first report of the direct observation of effects ascribable only to single atoms arose from studies of alpha particles by Lord Rutherford, who wrote in 1904 that "in the scintillations of zinc sulfide, we are actually witnessing the effects produced by the impact . . . of single atoms of matter. . . ." Somewhat similarly, in 1912 C.T.R. Wilson reported observing the vapor trails of single atoms as they traversed his cloud chamber apparatus. (Also in 1912, M. von Laue obtained his remarkable results on the diffraction of x-rays by the collective effects of scattering from all the atoms of a crystal, and a year later this effect was utilized by W. L. Bragg to provide direct and highly accurate measurements of the distances between the atoms within a crystal.)

Surprisingly, more than forty years would pass before the first photographs of individual atoms were obtained. In 1956, E. W. Muller used his field ion microscope to resolve the geometrical arrangement of atoms on the surfaces of sharply pointed tungsten wires (and, later, of atoms on other sharply pointed refractory metal wires). Subsequently, in 1970, A. V. Crewe and his associates demonstrated that photographs of individual heavy atoms on thin light substrates (carbon films) could be obtained with a scanning transmission electron microscope (STEM). Despite these successes, however, the nature of these two techniques did not allow the examination of most kinds of materials or the determination of their surface structures.

The most recent advance in this chain of accomplishments is the basis for the papers being published in this and the next issue of the *Journal*. The scanning tunneling microscope (STM), developed by G. Binnig, H. Rohrer, and their associates, goes well beyond the earlier achievements in several respects. It is much more versatile in the types of materials which can be studied and the range of conditions under which it will operate. Furthermore, it can be used to measure the positions of individual surface atoms with unprecedented three-dimensional resolution.

The number of difficult surface science questions that have been resolved with the STM is already large. It has been used to measure vertical position differences as small as 0.1 Å, and a lateral resolution that is better than 2 Å has recently been reported. This lateral resolution suggests that the electronic orbital of a single atom at the tunneling tip is involved. The STM technique has been applied to studies of the surface structure and topology of various metals, semiconductors, and biological materials. With the recent addition of the atomic force microscope to the STM family, the surfaces of insulators can also be examined (a different physical mechanism is utilized for atomic imaging and hence features not apparent in STM data may be detectable). The STM technique can be used from liquid helium temperatures to elevated temperatures, under various gas ambients, and even in a liquid environment.

In other types of investigations, the STM can be used in the "scanning tunneling spectroscopy" mode to study the electronic energies of both localized and delocalized states at surfaces, as well as work-function profiles. Potential distributions across resistive barriers can be measured. Fine lines can be formed in photoresist. And the STM can be used in a lower-resolution (nonatomic) mode to measure profiles, as first indicated in 1972 by R. Young, J. Ward, and F. Scire. Recent examples are its exploratory use in the examination of ultrasmall fabricated structures and of the surface roughness of critical materials or parts.

Thus the prospects for scanning tunneling microscopy are indeed exciting. It is our hope that these two issues of the *IBM Journal of Research and Development* will provide a worthwhile summary of this very dynamic and rapidly developing scientific topic.

Praveen Chaudhari

Vice President, Science
IBM Research Division