and yet another would try to predict the next word on the basis of the preceding phrase. Each one alone would reach tentative, incomplete conclusions. But together they could usually narrow down the possibilities enough to reach a satisfactory answer.

This multiagent approach has obvious parallels to human teamwork, as in, say, a panel of consulting physicians. To see how it might work in the example of a distributed air traffic control system, says Lesser, imagine that one radar installation has only an approximate idea of an airplane's position when it hands off control to the next radar down the line. The second radar could still use that information to narrow its area of search, improve its signal-to-noise ratio, and identify the airplane faster and more accurately than it could have on its own.

However, there is one major problem to this approach, Lesser admits, and that is global coherence. "How do you get each node to do the most fruitful thing for the overall activity?" he asks. The whole idea is to keep the processors from getting bogged down in communications and coordination. "But without a centralized view," he says, "you may have nodes doing redundant processing, or *wrong* processing." To reach some acceptable compromise, Lesser and his colleague Daniel Corkill are drawing on another mainstay of human organizations: put an overall structure in place to impose long-term coherence, and then give each node a certain range of responsibility within which it can make its own decisions.

The idea of computers forming organizations raises some fundamental research questions. For example, as things are now, the organizations are specified by the programmers beforehand. Can the computers be taught to organize and reorganize themselves on their own to fit the problem at hand? Lesser has been thinking about how to do that, but finds it slow going. "You find that the question of 'What is an organization?' is very difficult to define," he says. "Part of our work is to define a language in which you can talk about organizations symbolically." Malone has also been thinking along these lines. He and several colleagues have begun to develop an analytic framework for evaluating the efficiency and flexibility of organizations, including such factors as production costs, coordination overhead, and the vulnerability of the system to isolated failures or to sudden changes in the environment.†

Another research question: How can one machine reason about another's knowledge, intentions, and beliefs? "In human communication, a lot of what I say depends on what I believe about your state of mind," says MIT's Randall Davis, who organized the AAAI panel. "For example, if I think you know about something, I won't bother to explain it to you. If I think you don't believe it, I may argue for it." Exactly the same kind of considerations come up when machines have to communicate.

Michael Genesereth of Stanford University has been looking at some of these issues by mathematically modeling groups of computers, or "agents," that interact according to rules based on game theory. "The thing that intrigues me," he told the AAAI, "are the circumstances in which cooperation will emerge spontaneously from individual agents.

The simplest case is when the agents cannot communicate with each other, he explains. As long as the agents know about each other's desires and intentions, they still end up cooperating simply because that is the way they can best achieve their individual goals. "What we've found is that rationality necessarily leads to cooperation," he says.

On the other hand, says Genesereth, things begin to get very interesting indeed when the agents *can* communicate. Sometimes they cooperate. Sometimes they establish ad hoc organizations. But sometimes they try to manipulate each other. Sometimes they withhold information. And sometimes they lie. Genesereth hopes to do a lot more work in understanding why and when this happens.—**M. Mitchell Waldrop**

†Thomas W. Malone and Stephen A. Smith, *Tradeoffs in Designing Organizations: Implications for New Forms of Human Organizations and Computer Systems* (CISR WP #112 and SLOAN WP #1541-84, Center for Information Systems Research, Massachusetts Institute of Technology, Cambridge, March 1984).

High Spatial Resolution Ion Microprobe

With focused scanning ion beams, researchers can now make elemental maps with 400-angstrom resolution by secondary ion mass spectrometry

Photons and electrons are the mainline tools for imaging and analyzing the composition of solid samples, but ions can be used just as well. In mid-July at the 31st International Field Emission Symposium held in Paris, Riccardo Levi-Setti of the University of Chicago described the current state of the art: a scanning ion microprobe that has produced elemental maps with a spatial resolution of 400 angstroms by means of secondary ion mass spectrometry. The instrument can also make scanning electron microscope-like images at the same level of detail.

Researchers are lining up at Levi-Setti's door with proposals for collaborations. But it may not be necessary to fly to Chicago to find a high-resolution scanning ion microprobe. The flip side of imaging is pattern generation. Microelectronics researchers, especially those in Japan, are investigating ways to use scanning ion beams to draw the fine features of integrated circuits. Spurred primarily by this interest, several companies are or soon will be marketing scanning ion beam machines with promised resolutions as high as 500 angstroms.

At Chicago, Levi-Setti has been interested for several years in high-resolution ion microscopy by means of focused scanning ion beams. However, it is not images but the ability to make spatially resolved elemental analyses (microanalyses) at the submicrometer level that has researchers scrambling to use the scanning ion microprobe. Frederick Coe of the Chicago Medical School, who is collaborating with Levi-Setti on projects to study developmental processes in the skull bone (calvarium) of the fetal rat and to investigate the microstructure of kidney stones, says that the ability to map the presence of individual atomic species or especially isotopes of the same atom with submicrometer resolution is the key. "Otherwise I would just use [a scanning electron microscope]."

Microanalysis by means of the x-rays emitted when a scanning electron beam strikes a solid surface is the standard laboratory method. Although the resolution for imaging is fixed by the diameter of the electron beam and can be as small

as 10 angstroms, the same is not true for the analysis. The primary electrons in the beam randomly scatter off atoms in the sample. These electrons can migrate a micrometer or so in all directions before stimulating x-ray emission, which sets the resolution for analysis.

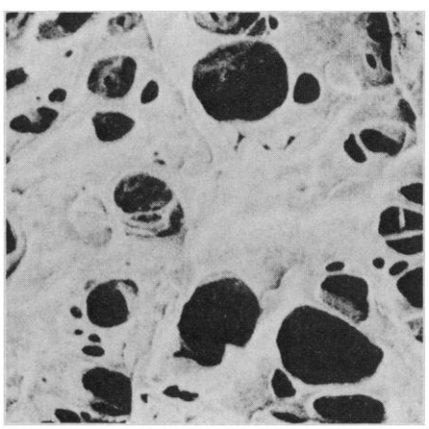
With scanning transmission electron microscopes, it is possible to do much better, either by analyzing the x-ray fluorescence or by measuring the energy loss of the electrons transmitted through the sample. However, the spatial resolution of 50 angstroms or less comes at a price. It is necessary to thin the sample to a dimension no more than ten times the desired resolution to avoid the scattered electron problem.

Being much heavier than electrons, ions do not scatter nearly so far and therefore have the potential for a higher spatial resolution in microanalysis. Secondary ion mass spectrometry (SIMS) is a well-entrenched technique in which a bombarding ion beam blasts atoms and molecules loose from a 5- to 8-angstrom-thick layer at a solid surface. By a charge exchange process, these species become ionized while still near the surface, and the ions can be collected and focused at the input of a mass spectrometer.

One researcher who appreciates the high-resolution SIMS capability is David Hwang of AT&T Bell Laboratories, another early collaborator at Chicago. Hwang wants to investigate phase transitions in intercalated graphite. Elemental or molecular species are stuffed in the spaces between the graphite planes, where they become a two-dimensional system of the type of much interest to physicists these days. At high temperatures, they have a disordered structure. But when cooled, they condense into a multiphase system comprising, for example, small islands (500 angstroms) of disordered structure in an ordered sea. Moreover, the compositions of the ordered and disordered regions may be different. Hwang is relying on the scanning ion microprobe to study the chemical segregation of elements between the disordered and ordered phases.

How does one obtain and display the results of chemical analysis of many small areas, such as the matrix of 1000 by 1000 picture elements in the field of view of the Chicago scanning ion microprobe? The smallest picture element in this instrument is an area 400 angstroms in diameter, and there are not enough atoms in a surface layer this size to make a detailed mass spectrum. Even if there were, it would be impractical to make 1 million spectra. Moreover, most of the time researchers need to track only a few elements of special interest. The usual approach is to get an "image" of the sample in which the brightness at each point represents the concentration of the element of interest (elemental map) by setting the mass spectrometer to accept only the element of interest while the sample is scanned.

Among the examples in the paper, coauthored with Yuh-Ling Wang and Geoffrey Crow, presented at the field emission conference, Levi-Setti showed a survey mass spectrum obtained in 42 minutes by averaging over a large area (200 micrometers by 200 micrometers) of a polished section of stony meteorite obtained from Edward Olsen of the Field Museum of Natural History in Chicago, another Levi-Setti collaborator. The meteorite is of the type thought to have formed in the solar nebula prior to the evolution of the planets (Mezo-Madaras unequilibrated chondrite). He followed this with detailed maps of the distribution of sodium-23, magnesium-24, aluminum-27, and iron-56 in smaller areas. The time required to make a map depends on the efficiency with which the ion beam removes a particular element from the surface, which varies considerably in SIMS. These maps each took 8½ minutes or less.



Rat calvarium

Sodium-23 elemental map of skull bone of neonatal rat. Picture is 25 × 25 micrometers.

Despite the absence of much ion scattering, commercial scanning SIMS instruments have until recently been limited to spatial resolutions of a few micrometers because of ion source limitations. Sources for high-resolution work face some stiff requirements. They must emit enough ions to make imaging and analysis possible in a practical amount of time, and they must emit into a small area for high resolution. Older sources have had high current but emitted into a large area. Newer liquid metal ion sources that are 1000 times brighter because of their small size are allowing the submicrometer barrier to be broken and thereby vastly broadening the domain of SIMS applications.

As it happens, the Chicago group is not the first to mate liquid metal ion sources with SIMS capability in a scanning ion instrument, but it has concentrated the hardest on high resolution. Earlier reports include those from Philip Prewitt and Derek Jefferies of the Culham Laboratory in the United Kingdom, A. R. Waugh, A. R. Bayly, and K. Anderson of VG Scientific Limited, also in the U.K., and Jon Orloff and Lynwood Swanson of the Oregon Graduate Center in Beaverton, all of whom used liquid gallium, and F. G. Rüdenauer of the Austrian Research Center Seibersdorf in Vienna and his several co-workers, who tried liquid indium. The work at VG has led to commercial instruments, some of which have a 500-angstrom spot size in their specifications.

Chicago's new scanning ion microprobe is one of two built at the Hughes Research Laboratories in Malibu, California, during the course of a 4-year collaboration between the two institutions. The second instrument remains at Hughes, where microelectronics applications are the main interest. Key features of the machines are a design for a system of electrostatic lenses (ion optics) that collects, accelerates, and focuses the beam on the sample, a high-efficiency ion collection system for SIMS, and a liquid gallium ion source of the type developed by Robert Seliger, J. William Ward, Victor Wang, and Randall Kubena at Hughes in 1979.

Field ionization sources, of which the liquid metal sources are an example, have always been important for high resolution. For example, the first Chicago scanning ion instrument was built in the mid-1970's by William Escovitz, Timothy Fox, and Levi-Setti around a gaseous hydrogen source. The gas flows by a fine (1000 angstrom) tungsten wire tip which has a few thousand volts applied to it. The intense electrostatic field ionizes the gas and starts a stream of protons toward the ion optics. A spatial resolution of 1000 angstroms was achieved in imaging, and there was no SIMS capability.

A distinct improvement came after the development of the liquid gallium source, to which several groups contributed, including Roy Clampitt and Jefferies at Culham, Victor Krohn and George Ringo of Argonne National Laboratory, and Orloff and Swanson of the Oregon Graduate Center. The advantage of the liquid metal source is that the emitted

current per unit solid angle is increased by a factor of 20 over that from the gas source because of the greater density of the liquid.

The metal coats the tip of a wire, which can be rather blunt, and the field draws the liquid into a characteristic cone from the tip of which the ions are emitted. Recent theoretical work by Nian Kang, David Kingham, and Swanson at Oregon seems to settle in favor of field evaporation a dispute between proponents of the views that metal is first thermally evaporated from the 20-angstrom-diameter tip and subsequently ionized by the field and that ions are directly produced at the tip surface by field evaporation. Although many metals and alloys are now used, gallium is conveniently liquid near room temperature.

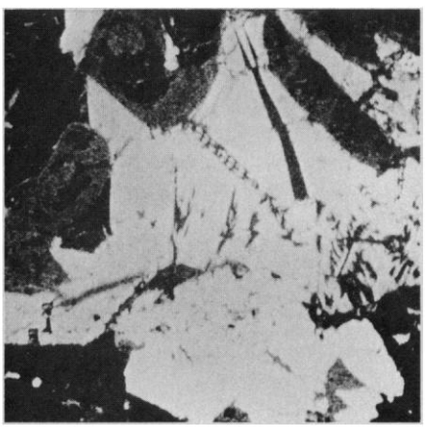
A disadvantage of liquid metals is that the ultimate spatial resolution is poorer than that of gases. The electric field lines near the tip and hence the trajectories of the ions must be perpendicular to the electrically conducting liquid metal cone. The apparent size of the source (virtual source) to the ion optics is the diameter of the region from which the ions seem to originate after their trajectories have bent toward the sample, which, according to experiments by Masanori Komuro and his co-workers at the Electrotechnical Laboratory in Ibaraki, Japan, is about 400 angstroms.

Virtual source size was not yet the limiting factor, however. Resolution remained at 1000 angstroms in the scanning ion system in which the Hughes researchers incorporated their source and in the Chicago instrument retrofitted with a liquid gallium source. Levi-Setti and Fox then set about designing an ion optical system capable of 100 angstrom resolution, which is the one in the Chicago/Hughes scanning ion microprobes.

Getting below a 1000-angstrom resolution is partly a matter of care and partly a matter of trading off conflicting priorities. Ion optical systems have "chromatic aberrations"; that is, their focusing depends on the energy spread of the ions. Ion sources emit particles with a distribution of energies. The resulting loss of resolution depends on how great the spread of ion energies is. Levi-Setti says that the elimination of chromatic aberrations is in principle feasible, but it is an expensive last resort.

The Chicago/Hughes scanning ion probes have a system of two three-electrode lenses, as compared to a single lens in many earlier systems, and this already helps considerably because of a second optical property—the magnification, which refers to the change in the size of the ion beam as it goes through the optics. Most instruments have had a magnification of 1 or 2, but with a lower magnification, the size of the image of the source decreases and the resolution gets better in proportion. The Chicago/Hughes scanning ion probes have a magnification of about 0.3, when in normal operating conditions.

One trade-off is between resolution and ion current. For example, one puts an aperture ahead of the optics that defines the beam. It is always possible to reduce the aperture, which lowers the beam diameter at the expense of current. Moreover, everything that limits resolution gets worse as more current is drawn from the source, so the designer wants to find the optimum condition of a usefully high current and livable resolution. Levi-Setti and Fox chose to emphasize resolution over current.



Meteorite

Sodium-23 elemental map of polished section of Mezo-Madaras unequilibrated chondrite. Picture is 45 × 45 micrometers.

It may be possible to do better in the not too distant future. By means of an even smaller aperture, says Levi-Setti, a beam size of 100 angstroms may be obtainable. Going much smaller than that is not likely to be attempted, since ion scattering causes secondary ion emission to take place over this distance.

A new source may also help. At the National Research and Resource Facility for Submicron Structures on the Cornell University campus, Gary Hanson has been working on a molecular hydrogen ion source. The wire tip is to be maintained below 5 K, so that the hydrogen condenses. Tiny structures grow on the condensed hydrogen layer that give at least as high a current density as the liquid metal sources, but have a virtual source size closer to that of gaseous sources. Moreover, the range of energies in the ion beam is a factor of 5 smaller than in either the gaseous or liquid metal sources, which means chromatic aberrations are less. However, some practical problems, such as reliably reproducing the tiny structures, still remain.

While the new scanning ion microprobes were under development, the Chicago group busied itself with testing the imaging capabilities of its older instrument with the liquid gallium source. Two imaging modes were explored. In one, secondary electrons escaping from the surface are collected as in a scanning electron microscope. In the other, the secondary ions dislodged by the primary ion beam are collected. Both of these imaging modes have been retained.

For SIMS work, the sample chamber gets crowded. The secondary ions are immediately energy analyzed by an electrostatic prism, and the monoenergetic ions then travel through transport optics some distance to a radio-frequency quadrupole mass filter. The SIMS optics are important because the resolution of elemental maps will not approach the ion beam size unless good statistics (high count rates) are possible.

Complete scanning ion systems are available from a British company, VG Instruments Limited (Stamford, Connecticut), a Japanese corporation, JEOL (Peabody, Massachusetts), and an American firm, Ion Beam Technology (Beverly, Massachusetts). All are advanced two-lens systems, are aimed at microelectronics applications, and cost upward of $500,000. Only VG offers a SIMS capability right now. At least three other companies in the United States are planning ion beam instrumentation.

Alternatives to buying a system are to build one or to incorporate an ion source into an existing analytical instrument. Both VG and FEI Company (Hillsboro, Oregon) offer liquid metal sources with ion optics. One such effort is at the National Institute of Environmental Health Sciences in Research Triangle Park, North Carolina, where researchers want to extend the realm of SIMS microanalysis from elements to organic molecules on surfaces.

R. G. Stoll, D. J. Harvan, and J. Ronald Haas (now at the University of North Carolina) have built their own instrument from a commercial liquid gallium source with a beam size of 3000 angstroms and a high-resolution double focusing mass spectrometer to separate molecular fragments that have large masses but whose mass difference is small. Haas says that no effort at higher spatial resolution seems warranted for now because the power input to a smaller area would damage organic materials.—**ARTHUR L. ROBINSON**