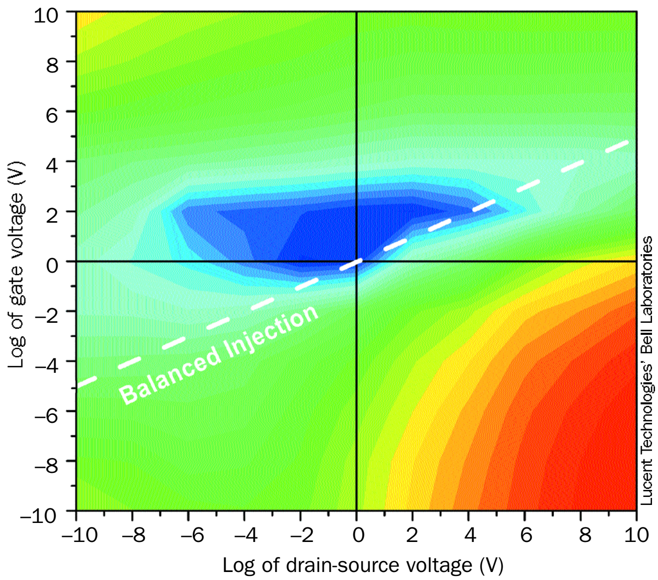
Light from organic transistors

By growing organic semiconductors on flexible plastic substrates, one can make them inexpensively and in larger arrays than conventional silicon-based semiconductors. So it comes as no surprise that researchers have sought displays based on such materials. In November, researchers at Lucent Technologies' Bell Laboratories (Murray Hill, NJ) announced a significant step toward that goal—the achievement of stimulated light emission from an organic field-effect transistor (FET) (*Science* 2000, *390*, 963).

FETs are standard transistors, but they are rarely used to produce light because they are generally "unipolar," that is, either electrons or holes can move and carry current, but not both. Because light is emitted when electrons and holes merge, it is essential to have both holes and electrons able to move freely. This is difficult to achieve, particularly in organic semiconductors. "Organics tend to have impurities that act as traps for electrons," says Hendrik Schön, one of the Lucent researchers.

Last July, the Lucent team produced a light-emitting, organic-semiconductor device by using high-purity materials and a complex six-terminal structure to control the flow of electrons and holes. But they knew that a practical device had to be much simpler. The new device is a three-terminal transistor made from a single crystal of alpha-sexithiophene (alpha-6T). In it, impurity traps are avoided, and a balance between electrons and holes is achieved simply by adjusting the two input voltages on the transistor.

When the voltages are properly balanced—that is, the drain voltage is twice that of the gain voltage—the electrons and holes flow toward each other and meet halfway between source and drain, where they combine and emit light. As the voltage applied to the transistor increases, the population of excited atoms increases. This increase results in the stimulated emission of light in which photons stimulate excited atoms to emit more photons, the basic phenomenon underpinning all lasers. The Bell Labs team observed the transition to stimulated emission at a very low current of 20 μA, which is comparable to the values for the smallest conventional semiconductor lasers. At that current, the transistors emitted light at 593 nm, in the yellow part of the spectrum.



Color plot of the channel conductivity of a transistor made from a single crystal of alpha-sexithiophene as a function of gate-source and drain-source bias (on a log scale) shows balanced electron and hole currents.

The next two steps in developing a practical device, according to Schön, are to create a resonating cavity (a pair of mirrors) to allow the laser amplification to build up, and an optical pathway to channel the light out of the plane of the transistor, where it is produced, to the perpendicular direction so it can be viewed or otherwise used.

The new FET would have several advantages if it could be fully developed. First, the same FETs could be used for control and data processing as for light emission, which would fully integrate the circuits that drive the lasers with the lasers themselves. Second, the structure would require no doping with additional impurities, which would cut production costs and allow the use of other materials that are not easily doped. In addition, like other organic semiconductors, alpha-6T crystals will grow on flexible plastic substrates and over large areas, making possible a range of new applications.

A city in the computer

In the 1980s, Carl Sagan and others warned that debris from a nuclear war could enshroud the Earth with a sun-blocking, life-destroying pall of ash. Physicists at Los Alamos National Laboratory developed complex emissions models to see to what extent this nuclear winter scenario was valid. Fortunately, the threat of such a grim phenomenon has greatly receded, and Los Alamos is applying some of the same algorithms to the more mundane and beneficial task of modeling traffic emissions for entire cities.

The emissions module is part of a giant traffic simulation program developed for city planners by 25 Los Alamos physicists, computer scientists, and mathematicians. In March, the team will complete a simulation of the Portland, Oregon, transportation system, including cars, trucks, buses, and trains. The simulation will enable planners to determine whether the city's future growth will allow them to meet required air-quality standards, and to assess the impact on traffic congestion of building a new highway, opening a new mass-transit system, changing zoning laws, and altering the distribution of industry.

The traffic model realistically replicates traffic flows, creating jams that correspond to actual congestion. "While earlier approaches to traffic used modifications of hydrodynamic equations, they never really worked because traffic flows are highly anisotropic—not the

Image not available

Los Alamos National Laboratory

This computer simulation by the Los Alamos team of traffic flow in Portland, Oregon, shows the number of people (reflected in both height and color) who plan to travel representative streets within a short time window.

same in all directions—unlike fluid flow," explains Chris Barrett, the team leader. Instead, the Los Alamos researchers found that a set of simple rules allowed a distributed computing system to accurately model the flow. Roads are divided into cells each 7 m long and 1 lane wide. In essence, the rules state that cars speed up until they reach the car ahead of them or attain the speed limit. They slow down slightly at random times. Somewhat more complex rules allow for lane shifting. Accidents are predicted by when the deceleration needed to avoid the next car exceeds the capabilities of a real car and driver, and are then modeled by making the cars that have collided stationary for a predetermined amount of time.

Although traffic flow can be modeled by relatively simple rules, the destinations of people and the times they travel are governed by the complex rules of human social interactions. To accurately model where people will travel, the team broke up the population of Portland into thousands of socioeconomic subunits based on income, age, and other characteristics. Using detailed surveys and land-use maps, they created a model of human travel behavior that includes what proportion of the population would be taking their children to school, going to work, going shopping, and so on for every district of the city. This enormously complex model of human behavior allows the simulation to produce traffic-flow patterns and emission estimates.

Using a distributed computer network,the Los Alamos team has simulated the entire city of 2.5 million people with 1-s time resolution. Depending on conditions, the simulation can run up to 100 times faster than real time, modeling a 2-h rush hour in little more than 1 min. During the next 18 months, Los Alamos will be working with private companies to develop a finished program for the commercial market. Ω

Can electrons be split?

One of the stranger phenomena predicted by quantum mechanics, one Albert Einstein called "spooky," is quantum entanglement, a state in which one subatomic particle's characteristics depend on those of another. If two particles are in entangled states, measuring one will automatically and instantly determine the state of the other, even if the particles are far apart. The phenomenon is at the core of efforts to produce a quantum computer that, at least in theory, could crack any encryption system now in use by performing certain mathematical operations far faster than any conventional computer can.

But quantum entanglement remains a poorly understood state. For decades, physicists have pondered just what constitutes a measurement. Is it an interaction with a macroscopic system or an observation by a scientist? Does the wave function that determines the probability distribution of a particle's position or velocity collapse instantaneously during a measurement? Answering such questions could have a large bearing on the practicality of quantum computing.

Humphrey Maris of Brown University thinks he has found a system that could experimentally resolve some crucial questions vital to understanding quantum entanglement (*J. Low Temp. Physics* 2000, *120*, 173). On the basis of his calculations and previously unexplained experiments dating back to the late 1960s, Maris argues that under certain conditions in liquid helium, the wave function describing an electron can be split into two distinct regions. The two regions can then be moved away from each other, which produces an entangled state consisting of a single particle.

An electron injected into liquid helium at very low temperature forms a bubble around itself, a well-known process. If the electron is in its ground state, the bubble is a sphere, reflecting the shape of the electron's wavefunction or probability distribution. But Maris points out that if the electron absorbs a photon and moves to an excited state, the bubble assumes an hourglass form. Strangest of all, however, if the temperature is low enough and the pressure high enough, the fluid around the bubble will pinch the hourglass at the middle until it splits the electron's wavefunction into two separate, spherical bubbles. In effect, the single electron wavefunction is split in two, with a 50% probability of the electron being in either bubble.

The two electron bubbles are entangled

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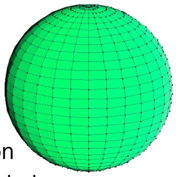
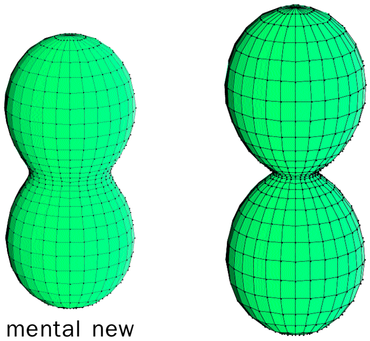


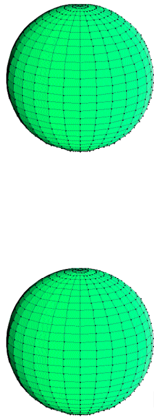
because a measurement indicating that the electron is in one of the two bubbles will, presumably, cause the other bubble to instantly disappear. In theory, if the bubbles could be separated, say in two containers of liquid helium, this would allow experiments to determine the speed at which the wavefunction collapses, and what constitutes a measurement. Oddly enough, quantum theory predicts that the collapse would happen instantaneously and could exceed the speed of light.

Such experiments could have major implications for quantum computation because it depends on keeping particles in entangled states until a measurement takes place. If, for example, bubbles could be maintained for long periods—separated yet entangled—it would considerably ease the problem of constructing a practical quantum computer. More speculatively, it could lay the basis for funda-



mental new methods of communication because the collapse of the wavefunction could be used to send a signal from one container to the other.

"What is important is that there is experimental evidence that appears to show that these split bubbles exist," emphasizes Maris. The split bubbles, which Maris dubs "electrinos," are smaller in diameter than the unsplit bubbles, 30 Å versus 35 Å. Their smaller size would allow them to move faster in an electric field, thus increasing the conductivity of the fluid. Experiments dating back to 1968 have shown that conductivity does, in fact, increase when the electron-containing helium is exposed to light, and, thus, in Maris's hypothesis, produced the split bubbles. No other theory



Brown University, Dept. of Physics

An electron in the 1s state in liquid helium occupies a spherical cavity that is set in motion when the electron is optically excited to the 1p state, leading to a breakup into two bubbles.

has successfully explained the photoconductivity effect or experiments that show some bubbles travel faster than others.

Some researchers remain skeptical of Maris's hypothesis, arguing that it would produce paradoxical quantum mechanics. But Maris is conducting new experiments that should determine whether electrons can split in two. If they can, decades-old questions about the nature of entangled states might be experimentally decided. Ω

Sunlight to hydrogen

Fuel cells that combine hydrogen and oxygen to produce electricity are often seen as the ideal energy technology for autos and other uses. They are lighter than batteries and produce no pollution. However, the source of the hydrogen is usually a fossil fuel, which makes the cells expensive to operate and fails to eliminate the need for producing oil or natural gas. Solar cells could produce electricity to split water into hydrogen and oxygen, but low efficiency has prevented commercial feasibility.

An international team of researchers from the Technion Institute in Haifa, Israel, the Nagoya Institute in Nagoya, Japan, and the Hahn-Meitner Institute in Berlin has shown that efficiency can be significantly improved (*J. Phys. Chem B 2000*, *104,* 8920). It has demonstrated a photoelectrolysis cell that combines the production of electricity and hydrolysis of water in one operation, which has a 50% greater efficiency than any previous such cell. The researchers believe that efficiency can be improved further, with up to 30% of solar energy converted to separated hydrogen.

The team began with high-efficiency solar cells that use two different semiconductors as a way to gather more solar energy. In such multibandgap devices, a high-bandgap material absorbs higher-energy photons, while lower-energy photons pass through and are absorbed by a low-bandgap material. As a result, less energy of each photon is wasted. In their experiment, the researchers used aluminum gallium arsenide and silicon layers that converted about 21% of sunlight to electricity.

The key to high-efficiency electrolysis was to match the output voltage of the cells (photoelectric potential) to the 1.229 V potential needed to split water. Such matching had to include consideration of the electrode materials as well. Platinum and ruthenium oxide electrodes catalyzed the hydrolysis reaction, and the accurate matching of potentials led to 90% of the electric energy being converted to hydrogen energy. The overall solar-to-hydrogen efficiency of 18% was far better than the previous record of 12%.

The team, led by Stuart Licht of Technion, points out that more-efficient but higher-voltage cells, such as gallium indium phosphide/gallium arsenide, can be matched to the hydrolysis potential. This simply requires putting two photoelectric cells in series to drive three hydrolysis cells, which would create a unit with an efficiency of 29% to 30%.

Even at 30% efficiency, however, solar-produced hydrogen will not be available at your service station any time soon. A station filling up 100 cars a day would need a football-field-sized solar cell to keep the hydrogen flowing.