like with a straw—not only water, but potentially other solutes also (*5*). It also confirms the well-known weakening of hydrophobic interactions upon cooling below room temperature (*6*).

Despite its obvious importance, physical insight into the origins of hydrophobicity is not easy to come by. Thermodynamic measurements are one approach, but interpreting their physical significance is extraordinarily subtle (*6*). Theoretical considerations and computer simulations show that a key concept is the size of the hydrophobic object (*7–9*). Water molecules can wrap efficiently around hydrophobic elements with a radius of curvature of 1 nm or less. When water meets hydrophobic surfaces that are flatter than this, it forms a molecularly thin cushion of depleted density between it and the hydrophobic surface.

The fly in the ointment is experiment. Putative depletion layers must fight against attraction of water to any hydrophobic surface, a ubiquitous force known as van der Waals attraction. This is probably why laboratory data have provided evidence both for [(*10*, *11*) and references therein; (*12*)] and against (*13*) this phenomenon. Despite that controversy, there is consensus that the expected thickness of a depletion layer is less than the dimension of even one water molecule. This small thickness matters for the following reason: If water meets hydrophobic surfaces softly, because van der Waals attraction outweighs its natural reluctance to do so, the frustrated interface should fluctuate wildly—as people also do, when they are unsure about what decision to make. Experiments (*1*) and theory (*14*) support this view, which merits further investigation.

But a caution is worth emphasizing: Hydrophobicity depends on the eye of the beholder. Some of the heated discussion in this field can be traced to the simple fact that people have different ideas in mind. One common definition is that water droplets on a planar hydrophobic surface possess a contact angle larger than 90°; but given that nothing dramatic changes when the contact angle falls below this or any other point, it is just a convenient but arbitrary definition. This has special relevance when seeking to distinguish between polar and hydrophobic patches on the surface contours of proteins. Many cases of modest hydrophobicity are akin to a bald man with a few thousand hairs on his head—he is on the bald side but others are much more bald. To understand better how hydrophobicity acts in the natural and technological worlds, and to overcome controversies, the following questions are worth future investigation. First, how does it matter whether a surface has the same wettability (hydrophobic or hydrophilic) everywhere, or is "patchy" from spot to spot? Answers will bring understanding in this field into closer contact with emerging issues in fields as diverse as protein folding and surface science.

Second, scientists have concentrated on systems that are subject to steady external conditions, such as a low temperature that causes proteins to denature. We do not yet have good ways to think about how aqueous systems respond to an extreme but perhaps transient change of environment. Is it realistic to expect a general theory of hydrophobic surfaces when temperature and pressure change in time and space? Empiricism shows that what matters is not just the instantaneous separation between hydrophobic surfaces but also the time (or frequency) of their contact (*1*); the timeline of change also matters.

Third: When does water act truly unlike other fluids? Spectroscopic studies of vibrations in water molecules are a technical tour de force but are problematic to interpret (*15*). Prevalent computational models use point charges and do not explicitly recognize quantum mechanics; it may be worth inquiring more critically into the assumptions made in these models. Moreover, too often the models are specific to the system under study, but common responses strongly suggest more universality. For example, when nanotubes fill with water at low temperature, one approach is to explain this in terms of the hydrophobic effect (*4*), but it can also be understood on the basis of more general principles of the competition between enthalpy and entropy (*16*). The challenge, then, is to predict from theory, rather than from empiricism, what makes water so special.

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10.1126/science.1167219

ECOLOGY

Crops for a Salinized World

Jelte Rozema[1] and Timothy Flowers[2]

Cultivation of salt-tolerant crops can help address the threats of irreversible global salinization of fresh water and soils.

Currently, humans use about half of the fresh water readily available to them to support a growing world population [expected to be 9.3 billion by 2050 (*1*)]. Agriculture has to compete with domestic and industrial uses for this fresh water. Good-quality water is rapidly becoming a limited and expensive resource. However, although only about 1% of the water on Earth is fresh, there is an equivalent supply of brackish water (1%) and a vast quantity of seawater (98%). It is time to explore the agronomic use of these resources.

Adding to the increasing competition for fresh water is the gradual and irreversible spread of salinization. Salinity is affecting fresh water and soil, particularly in arid and semiarid climatic zones. Ironically, irrigation has resulted in the accumulation of salt to above normal concentrations in the rooting zone of arable land, as high rates of evaporation and transpiration draw soluble salts from deep layers of the soil profile. The water and salt balance has also changed in regions where dryland agriculture—growing crops without

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irrigation in areas that receive an annual rainfall of 200 to 300 mm or less—is practiced following forest clearance [this allows salts present in the groundwater to reach the surface (*2*)]. In addition, continuous sea-level rise in a warming world threatens increased salinity in coastal lowlands. As fertile soils become salinized (*3*), the yield of conventional crops decreases. For example, a survey conducted between 1993 and 1995 in the Sacramento Valley in California (*4*) revealed a loss of 10% as the salinity rose by 1 dS m^{-1} (soil salinity is measured by its electrical conductivity in solution). The United Nations Food and Agriculture Organization estimates that there are currently 4 million square kilometers of salinized land, and a similar area that is affected by sodicity, a condition in which Na^+ ions represent more than 15% of the exchangeable cations (*5*). Of the 230 million ha of irrigated land, 45 million are affected by an increase in salt content [figures based on data collected more than 15 years ago (*6*)]. Soil salinization particularly affects economically less-developed countries with large and growing populations that are located in arid climatic zones (including Pakistan, India, Egypt, Tunisia, Morocco, Peru, and Bolivia), whereas more-developed regions are much less threatened by, but not immune from, salinity (*7*). Soil salinization in arid regions is practically irreversible because fresh water is not available to leach any accumulated salts. Even such leaching efforts are questionable because the salt-water created has to be evaporated if it is not to cause further damage.

A salty world. The effects of salinization (and increased flooding) in the Yenyening Lakes system in the Shires of Quairading and Beverley, Western Australia.

PHOTO CREDIT: TIM FLOWERS

The evolution of plant life on Earth started 3 billion years ago in saline ocean water. With the advance of land plants about 450 million years ago, primary adaptations of plants to the high concentrations of Na^+ and Cl^- (about 500 mmol per liter of seawater) were effectively lost (*8*). Today, only about 1% of the species of land plants can grow and reproduce in coastal or inland saline sites. Among these salt-adapted halophytes are annuals and perennials, monocotyledonous and dicotyledonous species, shrubs, and some trees. There is a wide range of morphological, physiological, and biochemical adaptations in such plants, which vary widely in their degree of salt tolerance (*9*). Only some are tolerant to seawater salinity; more halophytes resist lower salinity concentrations. Potentially, many of these salt-adapted plants could become salt-tolerant crops in a saline agriculture in which soil salinity is less than (perhaps half) that of seawater.

Halophytes can grow at rates comparable to those of conventional forage crops (*10, 11*) and under saline conditions, biomass of the former is comparatively greater than that of all our major crops. For example, *Salicornia bigelovii*, a potential oil-seed crop, produces about 18.0 tons/ha of biomass and 2.00 tons/ha of seeds over a 200-day growing cycle (*10*); by comparison, the average yield of sunflower across the world in 2007 was 1.2 tons/ha. Although the physiological adaptations required to tolerate salinity require energy and therefore might be predicted to reduce plant growth and yield, any decline in halophyte biomass production occurs at much higher salt concentrations than for conventional crops.

Modern agrobiotechnology might speed up the process of achieving conventional crops that are resistant to the high concentrations of Na^+ and Cl^- in saline agriculture. Indeed, biotechnology has generated traditional crops that are resistant to plant pests and diseases, such as genetically modified corn and cotton. However, over the past 15 years, the bioengineering approach has not delivered salt-tolerant cultivars of conventional crops such as wheat or rice for release to farmers. So, although between 1996 and 2006 there were more than 30 reports of transformation of rice with different genes aimed at increasing salt tolerance, transgenic salt-tolerant rice is not close to release. The likely explanation is that salt tolerance is a complex trait determined by many different genes, so that transformation of multiple genes into a plant is required (*12*, *13*).

Because salt resistance has already evolved in halophytes, domestication of these plants is an approach that should be considered (*12*, *13*). However, as occurred with traditional crops such as rice, wheat, corn, and potatoes, domestication of wild halophytic plant species is needed to convert them into viable crops with high yields. Such a process can begin by screening collections for the most productive genotypes. There are many uncertainties and risks: variable germination, propagation, plant diseases, scaling up, processing halophyte biomass, market demand, and economic competition with conventional bulk-produced raw materials such as potato, sugar beet, and sugar cane. The development of halophytic crops would also have to be undertaken with studies of hydrological and soil management of saline agriculture systems.

The use of saline water for irrigation is in its infancy, although experimental trials using seawater (*14*) and mixed saline and fresh water (*15*) have been conducted. A huge benefit of using saline water in agriculture is that seawater contains many of the macro- and micronutrients that are essential for plant growth and function. Seawater is a vast resource that is further supplemented by massive volumes of brackish groundwater (salt concentrations ranging from 1 to 50% of that of seawater) and waste water; all could be available for saline agriculture. Moreover, the number of halophytic crops that would produce an economically viable yield if irrigated with brackish water would be much larger than if seawater were to be used for irrigation, because there are many more halophytes and coastal plants that grow well with brackish water than grow well in seawater.

The benefits of saline agriculture encompass not only food products for human consumption and fodder crops for animals, but also renewable energy (biofuel and biodiesel) and raw materials for industrial use (*16*). This is particularly relevant because the traditional raw materials for energy production—oil, gas, and coal—are being depleted and are expensive. However, the relative costs of growing halophytes for bioenergy and biofuel—a process that would not compete with the growth of conventional crops and therefore not threaten the world food supply—requires evaluation. A further advantage of saline agriculture is that growing halophytes may be combined with aquaculture of sea

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fish and shrimp. In such sustainable marine agrosystems, inorganic nutrients from fish or shrimp ponds can be used to promote the growth of halophytes (*17*).

Worldwide, initiatives are being undertaken to develop saline vegetable crops, as well as crops for fuel and fiber (*18*). And in various countries, private companies and research groups are collaborating to develop technologies that combine saline agriculture with aquaculture. The concept of a saline agriculture has been long discussed (*19*), but the increasing demand for agricultural products and the spread of salinity now make this concept worth serious consideration and investment.

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10.1126/science.1168572

PHYSICS

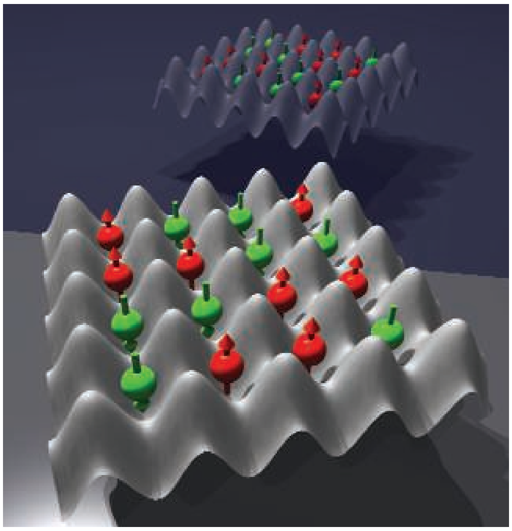
Controlling Cold-Atom Conductivity

Models of electron conductivity in solids can be studied with ultracold atoms trapped in artificial crystals by lasers.

L. Fallani and M. Inguscio

Why do some solids conduct electricity like a metal, and others act like insulators? Quantum mechanics has provided some relatively simple (and quite successful) models for electron conductivity, but the underlying physics is often complex, because electrons interact with each other through Coulomb forces and because real materials are not perfectly ordered. On page 1520 of this issue, Schneider *et al.* (*1*) address the microscopic distinction between a conductor and an insulator by examining the conducting properties of repulsively interacting ^{40}K atoms, which, like electrons, are fermions—they have half-integer spin and obey the Pauli Exclusion Principle, which allows only one fermion to occupy a quantum state. By placing ultracold ^{40}K atoms in an artificial crystal held in place through optical fields, they can manipulate the energy scales of the system so that it varies all the way from a metallic state to different kinds of insulating phases.

In the quantum-mechanical description of electron conduction, the translational symmetry of the crystalline solid also applies to the atomic orbitals of the weakly bound electrons of the constituent atoms. The electrons interact not with a single atomic potential but with a potential that extends over the crystal lattice. The energy states of the electrons cluster so tightly that they are almost continuous and are referred to as "bands." The highest-lying bound states form what is called the valence band, and the lowest-lying set of excited states forms the conduction band.



Quantum simulation of electronic conduction. Ultracold atoms in two different internal states (red and green) are trapped in a periodic structure generated by laser light (gray), forming a conductor or an insulator, depending on their energy and mutual interactions.

Electrical conduction can occur if electrons in a solid can occupy states in the conduction band, where they are free to accelerate under the action of an external electric field. In a metal like copper, the valence and conduction bands overlap in energy, so that the conduction band is partially filled by electrons from the valence band. Conversely, in a band insulator such as diamond, the valence band is completely filled, and a large energy gap separates it from the empty conduction band, which causes the material to be an insulator.

In real materials, this simple picture is complicated by additional effects, such as interactions between the electrons, which weakly repel each other, and the presence of disorder. When electron repulsion effects are sufficiently strong, the conduction electrons are forced far apart and localize in individual lattice sites, instead of having their wave function extended across the whole lattice, and a Mott insulator forms (*2*). When the translational symmetry of the lattice potential is broken by the presence of disorder, the electrons can move only in restricted regions of the crystal and again occupy localized states, and in this case an Anderson insulator forms (*3*).

The existence of these insulating phases was first predicted in the 1950s on the basis of simple theoretical models trying to capture the main mechanisms involved in electronic conduction in solids. However, a direct verification of these theories for electronic conduction has been hampered by the complexity of real materials—we cannot simply tune the potential created by the crystal lattice, nor the interactions between the electrons.

Fortunately, these theories are very general, and the ideas formulated for electrons can be verified in experiments in which clouds of neutral atoms are cooled down to temperatures

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