not a late add-on but there from the start. Children of that age are just beginning to segment words from ambient speech, although they are several months away from understanding or producing them (*6*). Marcus *et al.* used a common method in the study of infant cognition: present a stimulus repeatedly until the infants are bored, then present them either with stimuli of the same kind or of a different kind. "Same kind" and "different kind" are in the mind of the beholder, so if infants attend longer to the different kind, they must be telling them apart.

In these experiments, infants were habituated with "sentences" that follow one sequence, such as "ga ti ga" and "li na li" (an ABA pattern), and then were presented with sentences that contained different words and either the same sequence, such as "wo fe wo" (ABA), or a different sequence, such as "wo fe fe" (ABB). The babies listened longer to the "different" sequence, showing that they must have discriminated ABA from ABB; everything else about the test sentences, such as the actual syllables and their transition probabilities, was the same. Various controls ensured that the children did not simply like the sound of some sequences more than others, or memorize smaller chunks like BA. Marcus has also demonstrated that a kind of associative network frequently touted as a ruleless model of language learning, J. Elman's Simple Recurrent Network, does not discriminate the patterns in the way these infants do.

Marcus *et al.* (*1*) are careful not to claim that infants lack an ability to form associations, that rule learning is uniquely human, or that the rule-learning mechanism at work in this experiment is the same one that babies use to acquire language later. But their demonstration suggests that the ability to recognize abstract patterns of stimuli that cut across their sensory content is a basic ability of the human mind. How it is carried out in the brain is still largely a mystery. Research in the neurobiology of learning and in neural network modeling (perhaps searching where the light is best) has tended to focus on simple associative learning mechanisms whose functions would have been recognizable to associationist philosophers writing centuries ago. Marcus *et al.*'s experiment is a reminder that humans also think in abstractions, rules, and variables, and is a challenge to figure out how we do so.

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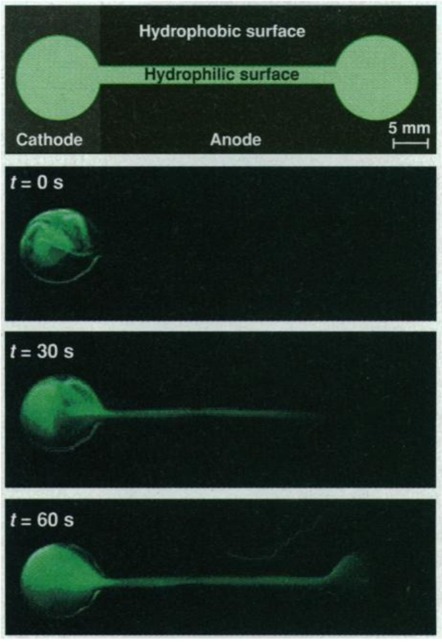
PERSPECTIVES: SURFACE SCIENCE

Driven Liquids

Michael Grunze

It has long been known that a continuous liquid film can spontaneously form into droplets that move freely over surfaces without application of an obvious external force. For example, wine connoisseurs are familiar with the "tears of wine" first explained by James Thomson in 1855 (*1*). The formation of wine drops from a continuous liquid film spreading over the wineglass surface is driven by the change in surface tension caused by the evaporation of alcohol. Variations in surface tension and the resulting changes in wetting behavior of the liquid by composition or temperature gradients were studied and explained over 100 years ago and are associated with the name of the Italian physicist Carlo Marangoni (*2*). Two reports in this issue, one by Gau *et al.* (*3*) on page 46 and the other by Gallardo *et al.* (*4*) on page 57, bring us up to date on recent studies of liquids moving on surfaces.

Spreading of a fluid or formation of drops from a continuous film is also controlled by the chemical composition of the substrate surface. Young's equation (*5*) defines the equilibrium contact angles through the interfacial tensions at the solid-liquid, solid-gas, and gas-liquid interface. The contact angle between liquids and solids can be used to classify a substrate with respect to its wetting and adhesion properties for technical applications (*6*), but it also indicates whether a surface will be resistant to the adsorption of macromolecules and particles of biological origin (*7*). A spatial inhomogenity in surface tension on a substrate to control adhesion and adsorption can be created by several approaches, such as by adsorption of hydrophobic molecules on a hydrophilic support (*8*) or by mixed hydrophobic-hydrophilic self-assembled monolayers (*9*). Nonequilibrium contact angles generated on opposite sides of a drop supported on a solid create a directional force and can even lead to the "uphill" movement of a droplet, as demonstrated by Chaudhury and Whitesides (*8*). Besides the obvious importance of surface tension in understanding interface phenomena, the practical control of wettability is elemental in the design and operation of microfluidic devices for microchemical analysis of complex fluids, flow cytometry, or rapid DNA screening. Any improvements in nonmechanical means to pump and position fluids are expected to have a direct impact on these emerging technologies.



Patterned pump. Time-elapsed photographs showing the pumping of green dye in a channel of liquid confined by a pattern of hydrophobic and hydrophilic self-assembled monolayers on a planar gold electrode. The gradient in surface pressure driving the flow is maintained by the generation and consumption of redox active surfactants at the cathode and anode surfaces, respectively.

The two reports in this issue describe how fluids and particles suspended in a liquid can be moved by spatially controlled changes in contact angles. Both reports explore the possibilities of controlling wetting and dewetting (and hence flow) by a structural control of the liquid-solid contact line, either by adjusting the volume of the liquid confined to a hydrophilic contact area or by manipulating interface chemistry by adsorption and desorption of surface active molecules.

Gau and co-workers (*3*) discovered a new general instability phenomenon for a

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liquid confined to a hydrophilic stripe in a hydrophobic surrounding. They studied the changes in shape of liquid stripes that were several micrometers wide in a periodic pattern as a function of their volume. With increasing volume, the fluid stripes of constant cross section undergo a transition to a state with a single bulge rather than into a row of individual droplets as would be expected from the classical Rayleigh plateau instability (*10*) of a free-standing cylinder decaying into a periodic array of droplets. The shape instability of the liquid cylinder confined to a hydrophilic surface area and the formation of a single bulge are explained by a theoretical model that contains no adjustable parameters and only depends on the two contact angles of the fluid on the hydrophilic and hydrophobic substrate areas. Swelling of the cylinders confined to a hydrophilic stripe implies that with increasing volume the contact angle at the boundary between the hydrophilic and hydrophobic surface areas does not satisfy Young's equation and hence the liquid channel becomes unstable.

No patterning of the substrate with hydrophilic or hydrophobic structures is needed by Gallardo *et al.* (*4*) to control the movement of organic or aqueous liquids or particles suspended in a fluid. Rather than patterning the surface energy of the solid support, Gallardo *et al.* control the surface pressure and consequently the movement of liquids and particles by creating and consuming surfactant molecules with redox active groups at electrode surfaces in their microfluidic system. Surface active molecules generated at one and consumed at the other electrode create a spatial gradient in surface pressure to guide droplets of organic liquids through the fluidic network. The velocity of the flow (in the millimeters per second range) is directly proportional to the voltages applied to the electrodes (hundreds of millivolts range). Gallardo *et al.* demonstrate these effects by pumping liquid crystal droplets that are not soluble in the aqueous electrolyte into different channels of a multielectrode array and by controlled dewetting of an electrode pattern that a priori has no spatial inhomogeneities in surface energy. When these principles are used for surfactant-induced patterned spreading of a liquid, this would allow one to control precisely the stability and position of a contact line and open the possibility of controlled mixing of fluids and chemical reactions in microscopic dimensions.

Current methods to control the flow of solutions or dissolved particles through a predefined channel network rely on electrokinetic phenomena requiring high voltages, mechanical actuators and syringes, or capillary wetting (*11*). In the work of Gau *et al.* (*3*), the curvature of the expanding liquid structure drives the flow of the fluid. When single bulges along liquid channels merge, the solutions mix and react through these interconnects. The electrochemical method developed by Gallardo *et al.* (*4*) does not even require a permanent channel system nor a hydrophilic-hydrophobic surface pattern to move suspended particles. Instead, a microelectrode array provides the means to direct flow in a continuous liquid film. Mixing by volume or electrochemical control rather than stirring or mechanical pumping provides novel cost-reducing design principles for microfluidic devices, in particular for disposable "laboratories on a chip," which are needed for a fast and inexpensive chemical analysis of complex fluids. And why should it not be possible to extend these nonmechanical fluid control principles to direct the flow of reactants into microreactors, to sort and separate proteins and cells, or to build temporary or permanent microstructures by spatially controlled reactions or deposition of particles?

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PERSPECTIVES: SUPERCONDUCTIVITY

Effective Mass and Color Change

M. V. Klein and G. Blumberg

There are sum rules in physics, consequences of fundamental laws and principles. The sum rules are exact expressions that relate sums of measured quantities to known parameters. These rules help scientists to study physical states of matter by analyzing how different measured constituents of the sum respond to external perturbations. On page 49 of this issue, Basov *et al.* (*1*) report new optical data on high–transition temperature superconductors that show how these nonconventional superconductors obey a sum rule in a novel way.

The optical conductivity $\sigma_1(\omega)$ describes the absorptive response of an electronic system to a weak electromagnetic field of frequency ω. The integral of $\sigma_1(\omega)$ over a finite range of ω defines the spectral weight over that range. When applied to a system of N_e electrons per unit volume in a solid, it obeys a fundamental sum rule for the total spectral weight:

$$S = \int_0^\infty \sigma_1(\omega)d\omega = \pi e^2 N_e/2m \qquad (1)$$

where e and m are the electron charge and the bare electron mass, respectively. Metals have one or more bands of quantum-mechanical states partially filled with electrons, the conduction bands, and many other bands that are either completely filled or completely empty. At low frequencies ω, $\sigma_1(\omega)$ will have contributions only from transitions within the conduction band ("intraband"), whereas at higher ω, "interband" transitions involving the other bands will also contribute to the conductivity. The interband transitions are expected for frequencies in the energy range from a fraction of an electron volt (eV) to many eV.

The two types of transition additively contribute to $\sigma_1(\omega)$, and thus, according to the sum rule, the constant S may be written as the sum $A + B$ of intraband (A) and interband (B) contributions. It is instructive to write A in the form of

$$A = \int_0^{\omega_c} \sigma_1(\omega)d\omega = \pi e^2 N_{ce}/2m^* \qquad (2)$$

where N_{ce} is now the density of electrons in the conduction band and m^* is an effective electron mass in the band—the bare electron mass renormalized because of electron-ion and electron-electron interactions. The effective mass describes electron motion and is related to dispersion in the conduction band. Here, we have assumed that the conduction band is sufficiently separated from other electronic bands so that a frequency ω_c can be chosen to separate these contributions. If ω_c and m^* are not changing as a function of temperature or applied perturbation, Eq. 2 is referred to as a partial sum rule, however, the sum A does not reflect any funda-

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