NANOELECTRONICS

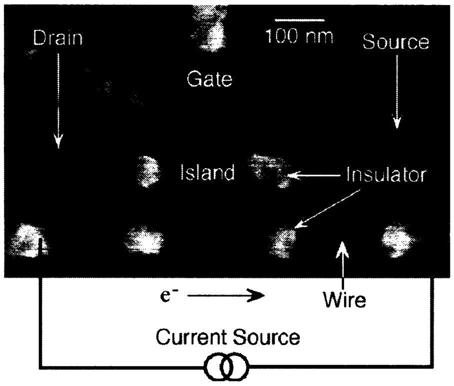
The Fastest Counter of the Smallest Beans

Imagine a device that could nestle close to a current-carrying wire and eavesdrop on individual electrons as they speed through it. The makings of such a device exist already: transistors so small that they deal in individual electrons. Such single-electron devices could serve as the heart of futuristic computer chips (*Science*, 17 January 1997, p. 303). But they could also serve as the most sensitive and accurate detectors of electrical current around, because the influence of individual charges passing through a nearby wire is enough to switch them on and off. So far, however, investigators haven't been able to exploit that promise, because they have lacked an amplifier fast enough to capture the rapid-fire signals from the transistor.

Now a team of U.S. and Swedish researchers has developed a new single-electron transistor (SET) architecture that includes an amplifier capable of recording the passage of electrons 1000 times faster than the previous record holder and about 1 million times faster than conventional SETs. The device, which the team describes on page 1238 of this issue, has drawn some rapid attention of its own, as it's likely to be fast enough to register individual charges in a current. "It's a real breakthrough in terms of speed," says John Martinis, a physicist at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Martinis says he and his NIST colleagues are working to define a new common standard for electric current by counting the number of electrons flowing through a device each second. "This certainly will help us," he says.

To come up with their high-speed SET, the transatlantic team, led by physicists Rob Schoelkopf of Yale University and Peter Wahlgren of Chalmers University of Technology in Göteborg, Sweden, modified a standard SET design. Conventional SETs are themselves an offshoot of ordinary transistors, which switch the flow of electrons through a semiconducting channel on and off by applying a voltage to a "gate" electrode above it. SETs replace the semiconducting channel with insulating material, except for a tiny semiconducting or metallic island halfway along. Now electrons must hop first through the insulator to the island and then hop to the other side. But if an electron is already on the island, its negative charge will repel subsequent electrons, in essence keeping them where they are.

A tiny voltage applied to a gate electrode over the island can increase the current through an SET, however. The voltage lowers the repulsive barrier felt by subsequent electrons, allowing them to jump onto the island and the resident electron to jump off. As a result, a stream of electrons passes through the channel, hopping one by one onto the island and off it again.



Current counter. A single-electron transistor counts electrons passing through a wire.

The same setup can be used as an electrometer to detect tiny amounts of current flowing through a wire. To do so, researchers simply place a wire next to the SET's channel so that it runs past where the gate would normally be. As electrons whiz down the wire past the gate's usual position, each one creates a tiny voltage increase that acts like voltage on the gate. These minute voltage fluctuations from the wire switch the SET on and off, allowing tiny amounts of current to flow through its channel—each burst of current registering the passage of an electron along the wire. The problem is that the rate at which electrons flow down the wire can be extremely fast, and conventional electronic amplifiers are too slow to register the SET's tiny signals.

To get around this problem, Schoelkopf and his colleagues connected an SET to a circuit known as a resonant amplifier. While the wire provides the voltage that turns the SET on and off, the resonant amplifier provides the impetus that pushes the electrons along the channel. An electromagnetic field that resonates at microwave frequencies within a circuit at the heart of the amplifier interacts with electrons to move them along. When the SET turns from off to on, this microwave energy pushes electrons through the channel, and the intensity of the microwave field resonating in the circuit drops—a change that is easy, and fast, to measure.

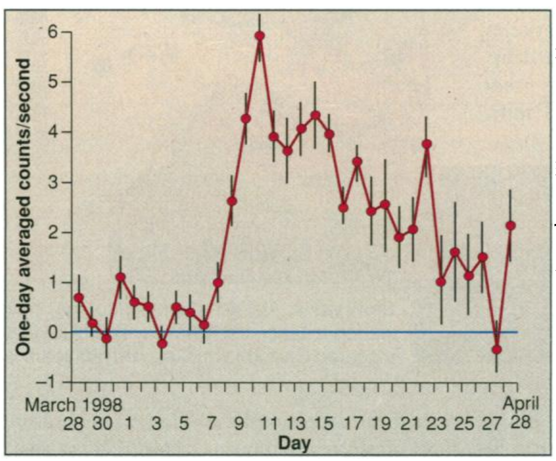
The resonator is able to detect signals from the SET at a rate of 150 million cycles per second. The group has yet to measure individual electrons flowing down a wire. But Schoelkopf is hopeful: "We can put this on a chip next to something we want to study and watch electrons as they flow by in real time."

–Robert F. Service

ASTRONOMY

A Neutron Star That Got Revved Up

Astronomers have discovered a "missing link" that could explain the formation of the bizarre celestial beacons called millisecond radio pulsars. Neutron stars that spin hundreds of times a second and give off a radio blip with each rotation, millisecond pulsars are thought to acquire their high revs when material torn from a companion star spirals in and applies a twist. New observations made by NASA's Rossi X-ray Timing Explorer (XTE) satellite seem to show just that: a neutron star that has spun up like a top and is spewing out x-rays as infalling material spirals down onto its surface.



Outburst. X-rays from a neutron star surged in April.

Rudy Wijnands and Michiel van der Klis of the University of Amsterdam analyzed XTE observations of an x-ray beacon that lies perhaps 12,000 light-years away in the direction of the galactic center, captured shortly after the satellite saw the object brightening around 9 April. XTE's detectors, sensitive to rapid x-ray flickers, showed that x-rays from the object slightly dim and brighten every 2.5 milliseconds, or thousandths of a second. The variation probably arises as the "hot spot" from infalling material whirls around with the neutron star.

"The missing link has now been found," says Frederick Lamb, a theorist at the University of Illinois, Urbana-Champaign. "It's kind of a dream come true." Wijnands and Van der Klis have reported their result in International Astronomical Union (IAU) Circulars and in scientific talks. Van der Klis declined to comment on it, however, because the team has a paper on the topic under review at *Nature*.

Radio pulsars are thought to consist of a spinning neutron star—a collapsed star about 10 kilometers across but more massive than our sun—sprouting a magnetic field about a billion times more intense than Earth's. Interactions between the whirling field and particles in the star's thin atmosphere generate radio waves, which stream like a lighthouse beam from the magnetic poles. Astronomers pick up a pulsar's radio blips each time a magnetic pole whirls past our line of sight, says Jonathan Arons of the University of California, Berkeley.

Ordinary radio pulsars, which were discovered more than 30 years ago, emit a blip every second or so. But in the early 1980s, astronomers detected a new class of pulsars that spin nearly 1000 times faster. In a widely held theory, says Arons, the stars "get spun up" to such fantastic rates by accreting matter from a companion at an earlier stage of their lives. As the disk of material spirals inward, it applies a torque to the pulsar's magnetic field, revving up the star.

Bursts of x-rays, emitting from the superheated material that crashes to the surface of the neutron star, should signal the spin-up. But until now, nearly all known x-ray pulsars have had periods longer than a second, probably because they have magnetic fields so powerful that they disrupt the disk of infalling material far from the surface of the star, where the disk is still spinning relatively slowly.

The rotation rate of the new object, SAX J1808.4-3658, suggests that its field must be weak enough to allow the disk to come within about 20 kilometers of the surface. An earlier sighting supports that assumption. In September 1996, the Italian-Dutch BeppoSAX satellite observed x-rays emitted by thermonuclear explosions on what was apparently the same object. The explosions are thought to occur when pressure builds up within a widespread puddle of accreted material on the surface of a neutron star. Such extensive puddles of unburned material could never form on a star that has a powerful magnetic funnel to confine the infalling material, say astrophysicists. "This object has a spin period and an inferred magnetic field that would most likely allow it to become a millisecond radio pulsar when accretion shuts off," says Lars Bildsten of Berkeley. "This is the first such example."

The rapid-fire x-ray pulses are only one sign of a millisecond pulsar being born. The midwife—a companion star—appears to be present as well. In a second result, reported in IAU circulars and accepted at *Nature*, Deepto Chakrabarty and Edward Morgan of the Massachusetts Institute of Technology describe slower variations in the x-ray emission, which seem to show that the pulsar is tightly orbiting a companion star. Chakrabarty, along with Paul Roche of the University of Sussex in the United Kingdom and others, may also have seen the companion star directly, through a ground-based telescope.

Radio astronomers will now watch to see whether a radio pulsar emerges as accretion onto SAX J1808.4-3658, which is now fading, falls off even further. Until then, the infalling material will snuff out the radio bursts. But already, pulsar specialists regard the discovery as a triumph for their theory—and for XTE. "It's one of the things we hoped for from the Rossi mission," says Lamb, "and it's delivered."

–James Glanz

SEISMOLOGY

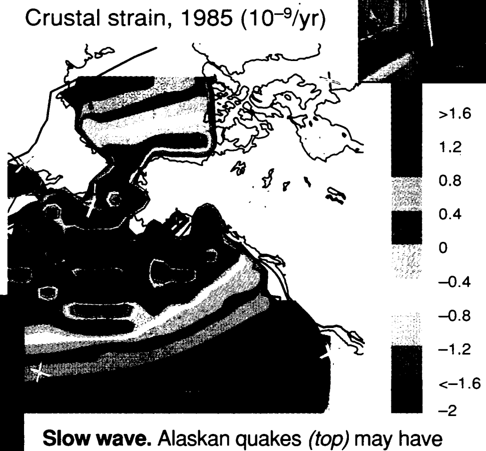
Can Great Quakes Extend Their Reach?

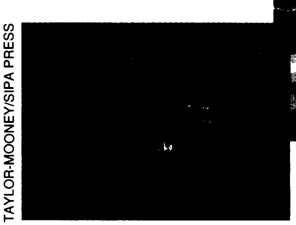
Earthquakes were once thought to keep to themselves, striking on a schedule determined only by the history of each particular fault. Then seismologists began to realize that every rupturing fault communicates with neighboring faults, instantly reaching out tens or hundreds of kilometers to hasten or delay distant earthquakes (*Science*, 16 February 1996, p. 910). Now a group of geophysicists suggests that these lines of communication extend even farther—and carry much, much slower messages.

Big quakes can trigger other quakes thousands of kilometers away and decades later, according to calculations presented on page 1245 of this issue of *Science*. Geophysicists Fred F. Pollitz and Roland Bürgmann of the University of California, Davis, and seismologist Barbara Romanowicz of UC Berkeley simulated how stress travels through deep, viscous rock. They found that the great earthquakes that struck the far North Pacific in the 1950s and '60s could have set off wave that triggered a pulse of seismic activity in California in the 1980s.

"It's an exciting possibility," says seismologist Thomas Hanks of the U.S. Geological Survey (USGS) in Menlo Park, California. If the reach of big quakes extends that far, seismologists may be able to make more sense of the comings and goings of earthquakes worldwide, he adds. Researchers are intrigued, though not yet completely convinced. "It could be right," says tectonophysicist Wayne Thatcher of the USGS, "but I think it has a ways to go before being a persuasive argument."

Researchers have long recognized a potential transmission route for long-distance messages among faults: the thin layer of soft rock at depths of 80 kilometers or more called the asthenosphere. There, temperature and pressure combine to soften rock so that, although still solid, it slowly flows over decades. The more rigid tectonic plates that make up Earth's surface, such as the great Pacific Plate, glide along on this softer layer.





Slow wave. Alaskan quakes *(top)* may have started a deep stress wave (deep blue) that triggered California quakes *(left)* 20 years later.

But plates don't slide smoothly at their edges. They stick to each other, build up stress, and then jerk forward in earthquakes. The quake redistributes stress nearby, adding stress in some places and relieving it in others. For example, between 1952 and 1965, four great quakes struck along the Aleutians and the Kamchatka Peninsula, where the Pacific Plate is diving beneath the North American Plate. After each quake, the Pacific Plate adjusted to the new plate positions immediately, stretching like a sheet of rubber and triggering flow in the asthenosphere below. Spreading outward through the asthenosphere like the ripple of a pebble dropped in a pond, the wave created by this flow could transmit the stress induced by the quakes.

"That [stress] wave has to exist," says Bürgmann. "The only question is how strong is it?" To find out, the group created a computer simulation of elastic plates, ductile asthenosphere, and large earthquakes in the northern North Pacific. In the model, the stress wave generated by the quakes moved southward across the Pacific and northward under the Arctic Ocean at a rate that depended on the viscosity of the