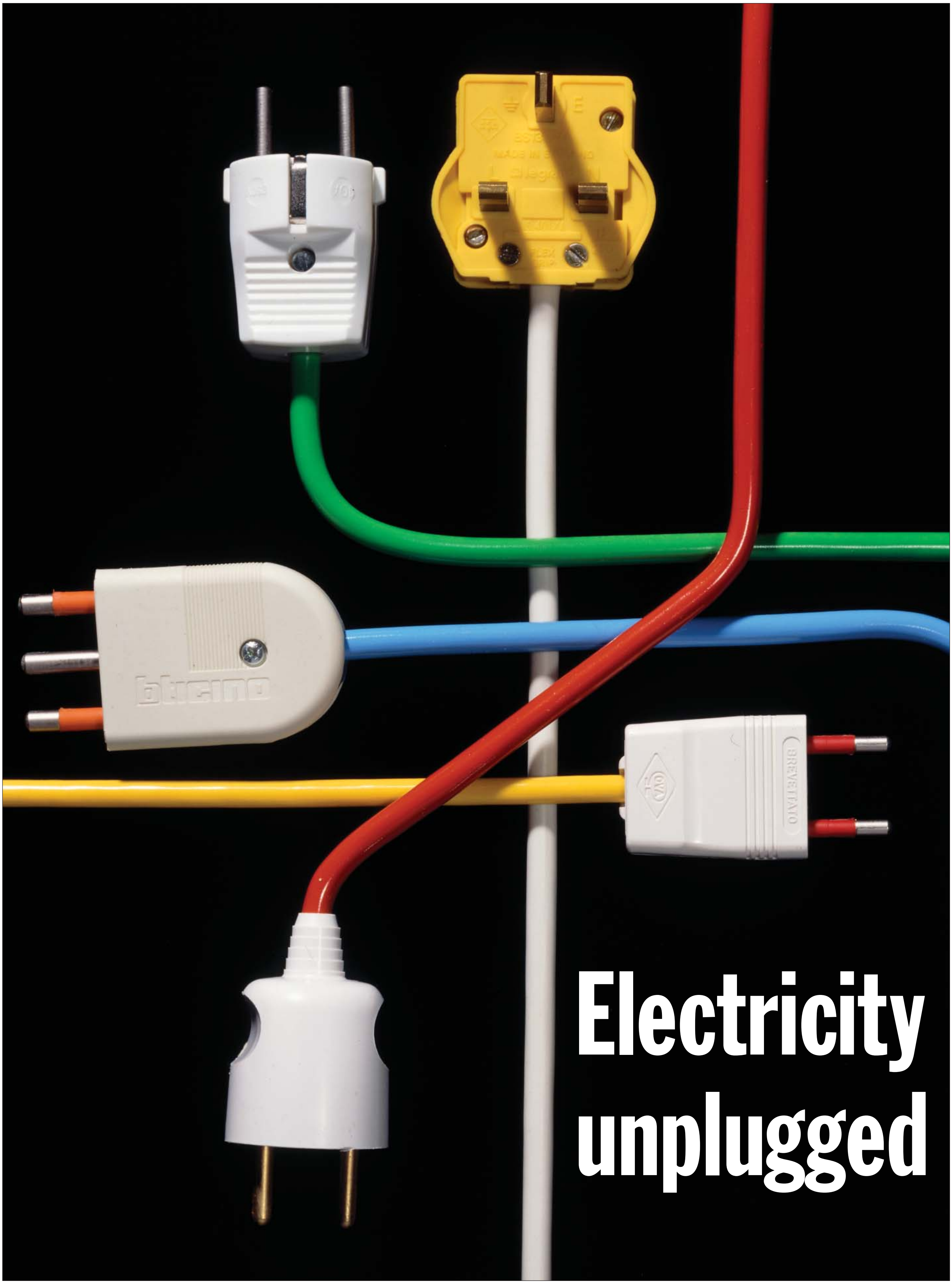


Electricity unplugged

Sheila Terry/Science Photo Library

In the near future, wireless electricity could replace the ubiquitous power cable. **Aristeidis Karalis** looks at a revolutionary new way of transmitting power without wires

Aristeidis Karalis is at the Massachusetts Institute of Technology in the US, e-mail aristos@mit.edu

The judge was driving back late one cold winter night. Entering the garage, the battery-charging indicator in his wirelessly powered electric car came on. “Home at last,” crossed his mind. He swiped his personal smartcard on the front-door detector to be let in. He heard a “charging” beep from his mobile phone. The blinking cursor on the half-finished e-mail on the laptop had been waiting all day on the side table. He picked the computer up and walked towards his desk. “Good evening, your honour. Your wirelessly heated robe,” said the butler-robot as it approached from the kitchen. Putting on the electric garment, he sat on the medical desk chair. His artificial heart was now beating faster.

Science fiction usually expresses society’s impeding desires and sense of anticipation for certain technological miracles to happen. A society without power cables is pretty much a given in most science fiction. Indeed, today we do live in the “wireless age”, in which the air that we breathe probably contains more information than oxygen. However, this is also an age where mobile phones, MP3 players, laptop computers and domestic robots exist alongside old-fashioned power wires and bulky batteries. Unlike information, electrical energy is still physically confined to these borderline anachronistic appliances. Overcoming these last obstacles would finally make this a truly wireless world. Science? Yes. Fiction? Not anymore.

It all started a few years ago when Marin Soljačić, a physicist at the Massachusetts Institute of Technology (MIT) in the US, was driving back home one cold winter night and he heard an unfriendly beep from his mobile phone. It was the annoying reminder that the battery was running out, once again. It then suddenly occurred to Soljačić how great it would be if the mobile phone could take care of its own charging. The next morning, he returned to his office at the MIT determined to find a solution to the problem.

An exhaustive literature search soon revealed that wireless transmission of power was not an original idea. Back in the 1890s Nikola Tesla, one of great pioneers of electromagnetism, was the first to envisage that electricity, then a newly found form of energy, should be delivered to every house, in every city, in every country on the planet. However, Tesla did not foresee that people would be willing to drag wires around the entire globe to use electricity. Instead, he dreamed of a way of transferring electrical energy wirelessly over long distances. This would be achieved using big, coupled electromagnetic resonators able to generate very large electric fields, which were meant to propagate most likely either via conduction through the ionosphere (presumably including gigantic sparks) or through the Earth (possibly via intermediate coupling to the Earth’s charge resonances, so-called Schumann resonances). The epitome of Tesla’s efforts to achieve his goal was Wardenclyffe Tower, a 57 m high structure in Long Island that was meant to deliver electricity to the entire planet. The construction was interrupted in about 1905, not because the method was considered impractical or dangerous, but because the funder, the famed financier and banker J P Morgan, was concerned that there would be no way to bill remote electricity users. Nowadays, more than a century after Tesla, electricity reaches nearly every home through a global electrical grid. Nevertheless, J P Morgan’s objections meant a premature end to the first attempt at wireless electricity.

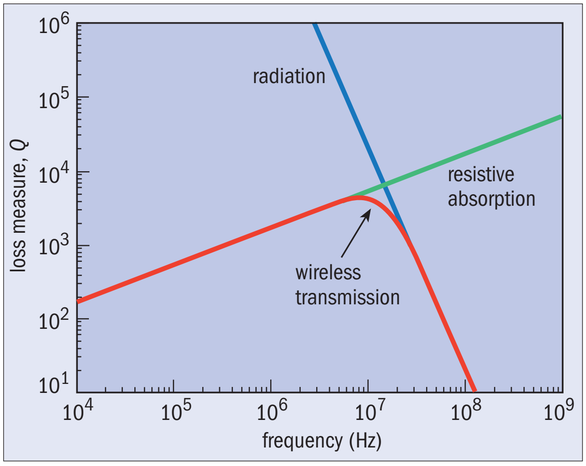
No wires attached

Today, we know of a variety of methods to transmit power without wires. The simplest example is electromagnetic radiation, such as radio waves. Omni-directional radiative antennas are one of the most widely used technologies, which are utilized in the provision of wireless Internet services, mobile telecoms, and radio and TV broadcasting. These antennas typically operate in the high-MHz/low-GHz frequency regimes. Even though such antennas are highly robust and suitable for use with mobile receivers, since they can operate in all directions and do not require a line of sight to the receiver, they are highly inefficient. Only a tiny portion of the radiated power in the direction of the receiver is actually picked up, since the vast majority of the radiation is lost in all the other directions. The use of a highly directional antenna, such as a microwave-beam antenna, in principle solves this problem and achieves a high efficiency in power transmission even over long distances (i.e. kilometres). On the other hand, this type of antenna does require an uninterrupted line of sight, which in itself requires a complicated device-tracking and beam-steering mechanism. Also, high-power focused beams may constitute a safety hazard.

An alternative approach to antennas is the use of an inductive transformer, a device commonly used in power circuits and electromechanical motors (for example electrical toothbrushes and chargers). A transformer typically operates up to mid-kHz frequencies. It essentially transfers electrical energy from one circuit to another via induction: the time-varying magnetic flux produced by a primary coil crosses a secondary coil and induces in it a voltage. The primary and the secondary coils are not physically connected, hence the method is wireless. Transformers can be very efficient but the distance between the coils must be very small (typically a few millimetres). For distances a few times the size of the coils, the efficiency drops significantly.

Part of the underlying physics for most of the existing methods for the wireless transfer of electricity is the fundamental principle of resonance: the property of certain physical systems to oscillate with maximum amplitudes at certain frequencies. It follows that, for any type of excitation (mechanical, acoustic, electro-

The fundamental principle of resonance is part of the underlying physics for most methods for the wireless transfer of electricity



Power up
The "quality factor", Q, of a coil (see main text for details) that can be used for wireless power transmission at frequencies of about 10^7 Hz when Q is at its peak, which is when the combined losses due to resistive absorption (green) and radiation (blue) are slowest.

magnetic, nuclear) with a given frequency, a receiver will pick up the transmitted energy efficiently only when designed to resonate at the excitation frequency. Only then do successive excitations after each oscillation period add coherently in phase and lead to a build up of energy within the receiver.

To illustrate, consider 100 glasses filled with wine at different levels so that they support acoustic resonances at different frequencies. Now let an electric-guitar player produce and sustain a very well-defined note. Only one of the glasses, the one resonant with the frequency of this note, will respond to the excitation, to the extent that it may even break, while the rest will remain unaffected. Similarly, we tune the electromagnetic antenna of a radio to be resonant with the frequency of the station we want to listen to. Many transformers used in power circuitry and elsewhere are also designed to employ resonance to enhance the power transmission.

Cutting the cord at MIT

Since these days electricity is delivered to pretty much every single house in the world, it is not necessary anymore to transmit electricity over large distances *à la* Wardenclyffe Tower. Transmitting electricity within a room, namely over distances a few times greater than the size of the receiving devices themselves (what engineers define as mid-range distances), is sufficient for most modern applications. Achieving this goal with satisfactory efficiency, safety and low cost remains an unsolved problem. That was the challenge for Soljačić and his collaborators at the MIT labs: John Joannopoulos, Peter Fisher, Andre Kurs, Robert Moffatt and me.

Revisiting the fundamental principle of resonance, we posed the question of which physical conditions maximize the efficiency of energy transfer between two resonant objects. The energy of any resonator naturally decays due to intrinsic energy-loss mechanisms (friction for mechanical resonances, radiation and resistive absorption for electromagnetic resonances, collisions with phonons and spontaneous emission for atomic resonances). Losses are typically quantified by the number of oscillation periods that it takes for the energy to decay by a factor of 2.72. This number, represented by the "quality factor" Q, is an intrinsic property of resonators and depends on the strength of the loss mechanisms. (As a simple analogue, water inside a bucket with a hole will leak out at a rate that depends on the size of the hole.)

Our chosen regime was at low-MHz frequencies when much longer loss-times are observed

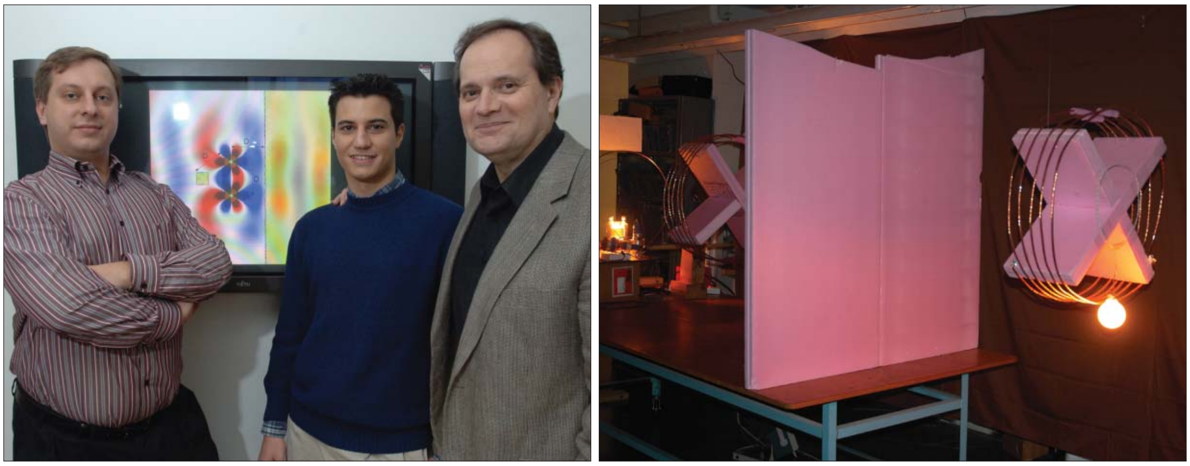
If two equal resonators exchange energy, it also takes a characteristic number of oscillation periods to transfer the energy from resonator A to resonator B, which is proportional to a constant that quantifies the strength of the coupling between the resonators, Q_{k}. (If water is pumped from one bucket to another via a hose, then the transfer time depends on the strength of the pump.) Clearly, for energy transfer to be efficient, Q needs to be much larger than Q_{k}, i.e. the rate at which energy is being transferred needs to far exceed the rate at which energy is being lost. (Water will be efficiently transferred between two leaking buckets if the pump is faster then the leaks from the holes.) The efficiency of the system can then be characterized by Q/Q_{k}. The transfer of energy is efficient only when this ratio is larger than one, the so-called strong-coupling regime.

For our wireless method, we used one of the most basic electric circuits as a resonator: the LC circuit. This circuit is an electromagnetic resonant circuit that consists of an inductor (L), made by a wire coil, and a capacitor (C). Two such wire coils transfer energy via induction, like a transformer device, and the Q_{k} clearly depends on the distance between the coils. For mid-range distances and long enough wavelengths, the spatial-decay rate of the magnetic field means that Q_{k} is roughly proportional to the cube of the ratio of the distance between the coils, D, and the size of each coil, d, while showing little dependency on the frequency and the geometry of the coils. This means that, for mid-range distances, Q_{k} will be large and the coupling very weak.

As a result, the best way to maximize the efficiency is to engineer the resonators to have the highest possible value of Q (try to seal the holes in the buckets). The resonance frequency of each coil (which has to be the same for both coils) can be tuned by varying the capacitance (and tuning a circuit element is exactly what the knob is tuning in a radio antenna). Q varies with the tuneable frequency, and this variation is shown in the figure above for a coil with a diameter of 60 cm made of copper pipe with a radius of 2 cm. It can be seen that, for high-MHz frequencies, the resonator loses energy fast (low Q, often even less than 10) due to radiation. This is exactly how an antenna is designed to work. Similarly, for mid-kHz frequencies, it loses energy fast (Q less than 100) via resistive absorption, which is typical of transformers. This explains why both omni-directional antennas and transformers fail to be efficient power transmitters at mid-range distances: the transfer-time measure Q_{k} is large because of D, and Q is small. On the other hand, in the intermediate, low-MHz regime, much longer loss-times are observed, with Q often larger than 1000. That was our chosen regime.

Based on our theory, we started experiments in late 2006. The main challenges consisted of designing a driving circuit that would operate in our desired low-MHz regime and constructing coils that would resonate with a high enough value of Q. After a trial-and-error phase, we realized that a simple coil design without a separate capacitor, but using the coil's self-capacitance to achieve resonance, was the best option in terms of Q.

We made two copper-pipe coils with 60 cm diameters and with five turns, such that they resonate at 10 MHz and have $Q = 1000$. A 60 W light bulb was our chosen



Donna Coveney/MIT

Wireless innovators Martin Soljačić (left), the current author (middle) and John Joannopoulos from the Massachusetts Institute of Technology, along with a lab demonstration of their technology – used here to light a 60 W bulb.

device, since it operates at the tested frequencies (and what can be a clearer sign of the functionality of a system than the switch on of a light bulb?). We suspended the coils from the ceiling with fishing wire, at a distance of 2 m from each other, tuned them up, turned them on and…there was light. At an efficiency of 45%, this was, to our knowledge, the first-ever demonstration of mid-range efficient wireless energy transfer.

On the safe side

The selective property of resonance means that almost all of the source power will be transmitted to the destined device and not to anywhere else. This is because any random object, including a biological organism, is almost always a non-resonant structure. Even if an object happens to be resonant, say a mobile-phone antenna, its resonance will be very different from the precise source-resonator frequency (just like those 99 wine glasses). Furthermore, even in the extremely unlikely case of it having the same resonance frequency, its Q value would be so low that no significant amount of power would be transmitted to it.

In our long-wavelength regime of operation (30 m wavelength at 10 MHz compared with 60 cm coils), power is transmitted from one object to another by spreading away from the source resonator and then “focusing” back into the device resonator. In contrast to higher frequencies, where power would be radiated across as a focused beam with a much smaller cross-sectional area, the former mechanism implies that, in our system, the power density locally and thus the fields will be considerably smaller at all points, except perhaps those too close to the coils. Smaller fields obviously imply safer performance.

Furthermore, our wireless-electricity method uses magnetic, rather than electric, fields to transfer energy. From the point of view of magnetic fields, most poor conductors, like wood, bricks, plastics and people, look a lot like air. On the other hand, electric fields do pose health hazards, because they can interact with biological organisms. With our method, these electric fields are confined to the capacitor inside our resonator. This method is quite similar to induction hobs on cookers, whereby a hob may transmit kilowatts of power to a metallic pot via induction, but it is safe to touch with our non-conducting hands. Note also that even the “large” magnetic fields in our system actually have tiny strength, approximately 10^{-4} T near the coils for 60 W of transmitted power, about the order of the time-invariant magnetic field of the Earth. It is the high-Q resonance that magically converts this tiny field into considerable usable power.

Wireless mobility

Long-wavelength fields naturally wrap and redistribute themselves around random objects in their vicinity or those standing between the source and mobile receiver. Therefore, while a radiated beam would immediately be interrupted by obstacles, our method stays robust and does not require an uninterrupted line of sight to the source. Sources can be hidden under floors, behind walls or inside furniture, and the receiving devices do not find shade while roaming freely behind random objects or when integrated inside other systems.

The near field produced by a resonant source coil spreads out quite uniformly in all directions, in contrast to a directed radiation beam. Thus, appropriate placement of one or more device coils can guarantee omnidirectional coverage with low system complexity and thus cost.

The response of the system to dynamic variations of its parameters due to variable interaction with its environment during motion can be as fast as within 0.1 ms, based on the available frequency bandwidth of the sharp MHz resonances. This is good enough for the changes associated with daily motion.

Ray Bradbury, the prolific science-fiction writer, once said that “Anything you dream is fiction, and anything you accomplish is science.” If our innovation is successfully commercialized, then the concept of a completely wireless world could soon leap from dream to widespread accomplishment. We will forget charging our mobile phones, laptops and other personal digital devices. The maze of cables behind every home or office apparatus will disappear. Cars will drive on electricity for much longer and more cheaply. Robots will completely forget about returning to their charging stations. Micro-robots will forever hide inside electronic chips. Battery-powered sensors buried underground will never die. And the story of the judge will soon belong to history.

“Dad, I found a lamp in the basement, but it doesn’t work, see?” said the 10 year old, while ascending the stairs. “It does my son,” replied the judge, “but it connects to a wall plug and our new house does not have any of those.” ■