it would be necessary to significantly increase the repetition rate of the laser, in order to increase the average flux of the photons.

The results of Schoenlein *et al.* open a new avenue for ultrashort x-ray sources, tunable in a broad spectral range. Especially attractive is the compactness and short pulse duration of this new x-ray source. Only a relatively low photon flux ($5 \times 10^4$ photons per pulse) has been obtained thus far, so only a very limited range of applications is currently possible. However, if this flux can be increased by several orders of magnitude, which is possible according to Schoenlein *et al.*, then a wide range of applications of such sources in industry, science, and medicine is possible.

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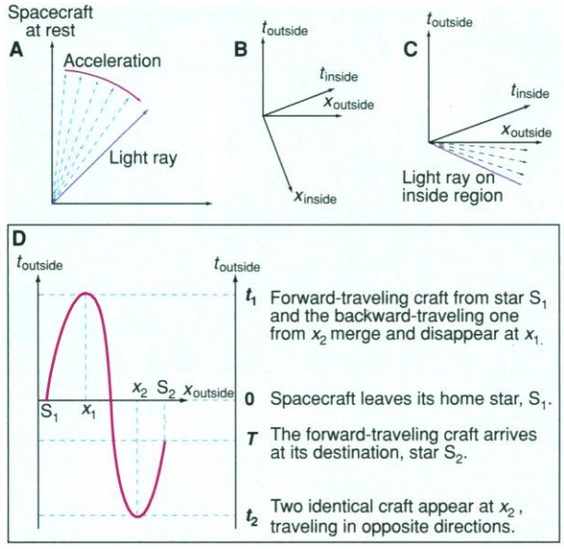
# A Warped View of Time Travel


Paul Parsons


Physicists have long known that it is possible to jump forward in time. Einstein's special theory of relativity predicts that a moving clock ticks slower than one at rest, a phenomenon called time dilation (*1*). Thus, a person in motion ages slower than someone who is not, which would allow a traveler to leave Earth on a fast spacecraft and return just hours later as measured in his or her own time but years later according to terrestrial clocks. The traveler would effectively have jumped forward in time. In recent years, several researchers have attempted to extend this concept to grant a hypothetical time traveler access to not only the future but also the past.

Special relativity accurately describes objects moving close to the speed of light but makes no provision for gravity. Einstein formulated general relativity, which builds in the gravitational force by bending the flat space-time of the special theory (*2*). Scientists have since found some novel time machines in curved space-time, involving exotica such as black holes, wormholes, and even cosmic strings formed during the earliest moments of the universe's history (*3*).

In 1994 Alcubierre used general relativity to propose a way of curving space and time around a spacecraft so that it could reach speeds arbitrarily greater than that of light (*4*). The gravity-free flat space of special relativity prohibits superluminal travel, but in the general theory, the story is quite different. The flexibility of space-time introduced by gravity allows it the freedom to stretch, causing relative motion between two otherwise stationary observers. Alcubierre found that there is no limit to the rate at which space can change its size and shape in this way. His model involves a hypothetical spaceship surrounded by a bubble of warped space-time. This bubble is capable of contracting the space in front of the craft and expanding the space behind it, the net effect being to sweep the vessel swiftly to its destination. In between the expanding and contracting regions and far away from the craft, space-time is flat; the spaceship and its crew as well as distant observers are safely situated in zero-gravity flat space, through which the bubble of warped space containing the spaceship can move at limitless speeds. Everett has now shown how this "warp drive" could be implemented as a time machine (*5*).




**A step back.** (**A**) Acceleration of a spacecraft from rest to speeds less than light (dashed lines). (**B**) The regions inside and outside of the "warped" region are both flat, and the axes are rotated relative to one another by their relative motion. (**C**) If the spacecraft accelerates to sublight speeds within the bubble, it is possible for it to travel backwards through $t_{outside}$ (dashed paths). (**D**) Time travel as seen by a distant observer.

In special relativity, the speed of an object is constrained to be less than the speed of light. Physicists represent this on a space-time diagram (see figure, part A), which shows time $t$, distance $x$, and the path of a light ray. A spaceship at rest would simply move along the $t$ axis. As it accelerates, its motion is described by one of the dashed lines, the direction of which rotates toward the light ray as the spacecraft travels faster.

With Alcubierre's warp drive, the situation is different. Inside the bubble, the spaceship is stationary with respect to the bubble and so moves along the $t_{inside}$ axis (figure, part B). As Alcubierre has shown, the inside region is allowed to move relative to the outside with an unbounded speed, which allows the direction of $t_{inside}$ to be rotated clockwise until it lies arbitrarily close to the $x_{outside}$ axis. In the inner flat region, special relativity holds, and the spacecraft is allowed to accelerate to any velocity less than light (figure, part C). Accelerating it to any one of the dashed trajectories takes its path across the $x_{outside}$ axis. An observer on the craft would then see $t_{outside}$ decrease; thus, time outside the bubble runs backwards.

Part D of the figure shows what this would look like to an outside observer of a spacecraft leaving star $S_1$, commencing time travel at $t_1$, finishing at $t_2$, and reaching star $S_2$ at a time $T$, less than zero. By reversing the roles played by stars $S_1$ and $S_2$, the ship can be made to travel in the opposite direction and arrive back at $S_1$ before it left. This suggests the intriguing possibility that engineers may one day be capable of building time machines without ever the need to harness exotic (and life threatening) astrophysical objects.

Aside from questions of technical feasibility, there are mixed reactions to some of the apparently bizarre consequences of time travel. Some argue for a "principle of self-consistency" (*6*), which requires all phenom-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ena, no matter how isolated, to fit into some global prescription that accounts for all the time machines in the universe. Such a law might arise naturally from the existing principles underpinning physics (*7*). Other researchers, including Hawking, assert that the paradoxes associated with time travel are so unacceptable that the laws of nature must somehow conspire to prevent it (*8*). If this "chronology protection conjecture" is correct, then it must also rule out the warp drive, which now comes complete with time travel, at no additional charge.

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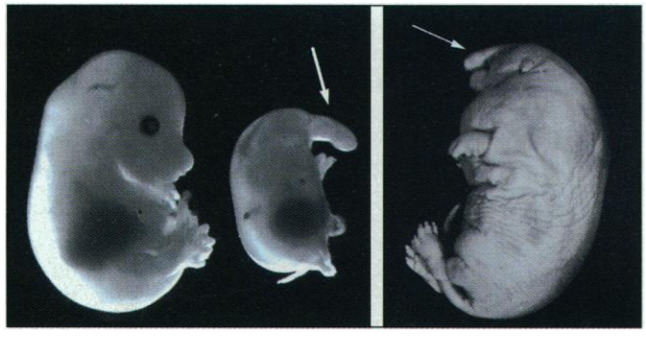
# Pass the Butter . . .

Gail Martin

After all the bad press that cholesterol has received for its contribution to human atherosclerotic disease, butter lovers everywhere can take some comfort in the findings of a report on page 261 of this issue. Cholesterol has a new—and vital—function: It is required for the normal action of a key patterning molecule in embryogenesis. Porter *et al.* (*1*) describe a remarkable autoprocessing mechanism that covalently links cholesterol to the secreted signaling molecule Hedgehog (Hh). This finding, together with data from another study by these authors (*2*), suggests an unprecedented mechanism for concentrating Hh and associating it with the cell surface, a key step in modulating its activity as a regulator of embryonic tissue patterning.

The story begins with the identification of the *hedgehog* gene in a screen for mutations in *Drosophila* that affect the establishment of the basic body plan (*3*). Once the *Hh* gene had been isolated, rapid progress was made in characterizing its roles in patterning the embryonic segments and larval imaginal discs (*4*). The story took on broader significance when *Hh* homologs were identified in zebrafish, chick, mouse, human, and other vertebrate species (*5–9*). Among the vertebrate *Hh* family members, *Sonic hedgehog* (*Shh*) has received the most attention because there is considerable experimental evidence that it is a potent regulator of tissue patterning in a number of developmental settings. For example, Shh protein can function as (i) the morphogen produced in the zone of polarizing activity that patterns the developing limb (*10*), (ii) the signal produced by the notochord and floor plate that induces somitic cells to adopt a sclerotomal fate (*11*), and (iii) the molecule that patterns the ventral neural tube and its derivatives (*12, 13*).

Genetic evidence that Shh performs these functions in the normal embryo has come from a study published last week in *Nature*, in which Chiang *et al.* (*14*) describe the phenotype of mice that lack a functional *Shh* gene. As expected, limb, axial skeleton, and ventral neural tube development are severely compromised in Shh-deficient embryos. However, the most striking external features of the mutant embryos are cyclopia and the presence of a single tubelike proboscis above the eye (see figure). These features, together with other midline facial abnormalities, are reminiscent of a spectrum of human congenital malformations collectively known as holoprosencephaly (*15*). They are indicative of a failure of the process of midline development that normally bisects the prospective forebrain, eye, and nasal territories, enabling them to develop into bilateral structures.



**Cholesterol's new job.** Abnormal head development (holoprosencephaly) occurs both in mice lacking the signaling molecule Sonic hedgehog (left panel, arrow; a control embryo is at left) and in rat embryos developing in females treated with inhibitors of cholesterol biosynthesis (right panel). This congruence is explained by the new finding in this issue, in which the lipid adduct of Sonic hedgehog, thought to be necessary for proper function, is shown to be cholesterol. [Left panel reprinted with permission from *Nature* (*14*); copyright (1996) Macmillian Magazine Ltd; right panel courtesy of C. Roux]

One of the most intriguing features of Hh family proteins is that they act as both short- and long-range patterning signals. For example, in vertebrates, floor-plate induction by Shh involves short-range signaling that depends on contact between the target neural plate and *Shh*-expressing cells (*8*). In contrast, motor neuron and sclerotome induction by Shh does not require cell contact and can occur over relatively long distances (several hundred micrometers) (*16, 17*). Likewise, in *Drosophila*, Hh can act as either a short- or a long-range patterning signal (*4*). One explanation for this duality in Shh's mode of action is that different concentrations of Shh have different effects on cells: High concentrations induce neural plate explants to form floor plate, whereas low concentrations promote motor neuron formation (*13*). The need for cell-cell contact likely reflects a requirement for a very high concentration of Shh protein, localized in or near the cells that produce it, whereas long-range signaling may be achieved by lower concentrations of protein that has diffused away from the producing cells. [However, in some instances, the long-range effects of Hh proteins are clearly due to induction of a secondary signaling molecule (*4*).] The mechanism by which Hh protein is concentrated and associated with the cell surface is of critical importance, because a cell that fails to retain Hh at sufficiently high concentrations presumably cannot participate in short-range signaling. Recently, considerable progress has been made toward understanding this mechanism.

Hh is synthesized as a precursor that undergoes autoproteolysis into an $NH_2$-terminal domain (Hh-N) with signaling activity (*18, 19*), and a COOH-terminal domain (Hh-C) that contains the determinants for autoprocessing of the precursor (*19, 20*). Recently, Porter *et al.* (*2*) showed that in addition to peptide bond cleavage, the processing reaction includes covalent linkage of a lipid moiety to Hh-N. The significance of the lipid modification is that it increases the hydrophobic character of Hh-N, thereby influencing its spatial and subcellular distribution. Consistent with the hypothesis that such processing is critical for Hh signaling,

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