pulsion, and Slit to Robo for silencing) allows the cytoplasmic domain of this coreceptor to bind to the cytoplasmic domain of DCC. Presumably, a different set of intracellular signaling proteins is then recruited to each receptor complex.

These new studies raise a number of important questions. Clearly, the most urgent need is to find out whether this silencing mechanism also operates in commissural axons in vivo. Fortunately, among their large collection of mutant and chimeric receptors, Stein and Tessier-Lavigne have generated a form of DCC that still mediates attraction by netrin but cannot be silenced by Slit. Coaxing commissural axons to express this unsilenceable receptor in vivo should reveal what role, if any, silencing might play in forcing axons to move on once they have reached the midline.

If, as seems likely, silencing does indeed occur in vivo, then it will also be important to figure out how commissural axons regulate their response to Slit—perceiving it first as a silencer, then as a repellent, and later perhaps even as a branching and elongation factor (*5, 14*). Regulation of Robo can only be part of the answer. In particular, Robo regulation cannot explain the different responses to Slit observed in stage 22 and stage 28 *Xenopus* spinal neurons. Perhaps commissural neurons change their responses to Slit according to some intrinsic program, in much the same way that they also change their neurotrophic requirements as they complete each leg of their journey (*15*).

The discovery of this silencing phenomenon also suggests an alternative explanation for the midline guidance errors observed in *slit* and *robo* fly embryo mutants. Could it be that axons stray across or linger at the midline in these mutants in part because of a failure to silence attraction, rather than simply because of a loss of midline repulsion as previously thought? Separating the silencing and repellent functions of Slit would help to resolve this issue. Stein and Tessier-Lavigne suggest a way to do just this: In the *Xenopus* assays, a mutant form of Robo that lacks the CC1 domain can still mediate repulsion but is unable to silence attraction. This mutant form of Robo has already been expressed in flies, and results in a low frequency of midline crossing errors (*16*). It is important to note, however, that *Drosophila* has two additional Slit receptors, Robo2 and Robo3 (*17, 18*). Both receptors contain the CC1 domain and so may also contribute to silencing. It will be interesting to see whether deleting the CC1 domains of all three Robo receptors leads to more severe midline crossing errors and, if so, whether these defects require netrin and DCC activity as predicted by the silencing model.

Finally, the studies of the Tessier-Lavigne laboratory force us to revise our view of how axons respond to multiple guidance cues. In vivo, axons are simultaneously exposed to a number of different attractive and repulsive forces. It has generally been thought that the axon integrates all of these signals in order to calculate its next move (*19*). But, as Stein and Tessier-Lavigne show, multiple guidance signals can also be combined in a hierarchical fashion, with one signal silencing the response to another. These two guidance strategies each make sense in different contexts. Integration, for example, has been most clearly demonstrated in the selection of different muscle targets by motor axons in *Drosophila* (*20*). Here, subtle differences in the way each axon responds to various muscle attractants and repellents may be an effective way to bias their preferences for specific muscle targets. In contrast, hierarchical guidance may be the better strategy at intermediate targets where axons must suddenly and drastically switch their preferences to ensure that they keep moving on toward their final destination.

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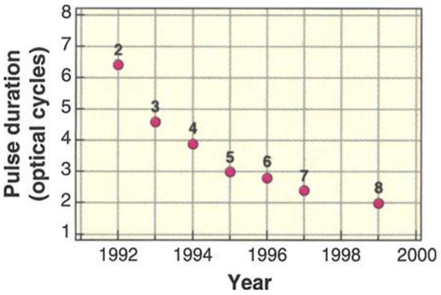
PERSPECTIVES: LASER PHYSICS

Toward Attosecond Pulses

Derryck T. Reid

In which scientific discipline would you expect to find the fastest recorded events? Surprisingly, the answer is not electronics, or even atomic physics, but optics. In the last decade, laser science has succeeded in generating pulses of light lasting less than 10 femtoseconds (fs), where 1 fs = 10^{-15} seconds. Femtosecond pulsed lasers have provided unprecedented insights into molecular processes such as reaction dynamics. So far, most research has concentrated on pulses in the visible or near-infrared part of the light spectrum. At these wavelengths, the optical wave takes about 3 fs to complete one oscillation, so that state-of-the-art 5-fs laser pulses correspond to less than two optical cycles. Optical pulses much shorter than this require substantial effort to produce, and, because light propagates as an oscillating electromagnetic wave, they are fundamentally limited to the "single-cycle" duration of about 3 fs.

Now, a new area of experimental physics is emerging, one sufficiently radical to be defined by its own prefix—attosecond science. By using femtosecond optical pulses to generate wavepackets in the soft x-ray region, where wave cycles last for only about 50 attoseconds (as) or 50 × 10^{-18} seconds, it should be possible to produce multicycle x-ray pulses with subfemtosecond durations. In this issue, Drescher *et al.* (*1*) report a first step in this direction. The authors have both created and measured x-ray pulses with durations below the carrier wave period of the original optical pulse.



Reaching a plateau. The steady decrease in the duration of optical pulses produced by femtosecond lasers over recent years has begun to slow down, implying that new approaches will be needed to produce subfemtosecond wave packets. The "single-cycle" limit for typical optical pulses has a duration of 2.5 to 3 fs and corresponds to the time taken for the propagating optical wave to complete one full oscillation. Numbers in the figure correspond to reference numbers.

Molecules are characterized by bending and stretching motions with time periods lasting several tens of femtoseconds or more, and femtosecond pulses can be used to study these vibrational motions. Measure-

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The author is with the Ultrafast Optics Group, Department of Physics, Heriot-Watt University, Riccarton, Edinburgh EH14 4AS, UK. E-mail: d.t.reid@hw.ac.uk

ments are made using the "pump-probe" technique, in which a strong "pump" pulse excites a collection of molecules into an initial energetic state, followed by a weaker time-delayed "probe" pulse that samples changes in the molecular behavior such as optical absorption. By recording many samples at different pump-probe time delays, one can construct a time-domain picture of the molecular response to excitation, which provides insights into its chemistry. The resolution of this technique depends directly on the pump and probe pulse durations, and therefore the extremely short pulses demonstrated by Drescher *et al.* offer substantially improved accuracy in these measurements. Furthermore, it might be possible to extend such studies to the analysis of atomic dynamics, which occur on much faster time scales than molecular vibrations. In their paper, Drescher *et al.* suggest that ultrashort x-ray pulses might be used to study the rapid motions of inner-shell electrons, which are tightly bound to the nucleus, or could provide information about fast ionization processes.

The route to attosecond science has been paved over the last decade by huge advances in the generation and manipulation of ultrashort laser pulses (*2*–*8*). Durations of optical pulses are now approaching a fundamental plateau at two optical cycles (see the figure), or about 5 fs for electromagnetic waves in the visible and near infrared. To achieve substantially shorter pulses therefore requires working at shorter wavelengths. Fortunately, it is possible to generate laserlike beams of x-ray pulses by focusing high-intensity ultrashort laser pulses onto a suitable target, such as the neon gas cell used by Drescher *et al.* The mechanism by which short optical pulses can generate even shorter x-ray pulses relies on the principle of harmonic generation. Any mechanical system that experiences a restoring force dependent on its displacement from some equilibrium position can oscillate at a well-defined resonant frequency. An isolated atom is one example of such a system, in which the outer electrons experience a restoring force due to the nuclear Coulomb field. These electrons are easily perturbed from their equilibrium position by a strong optical field, and the combination of restoring and applied forces results in complex motion involving frequencies much higher than that of the incident wave. As they respond to these forces, the electrons dissipate energy as high-frequency electromagnetic radiation, and wavelengths in the x-ray region are generated at harmonics of the original optical frequency.

In their experiment, Drescher *et al.* isolated the highest frequency harmonics and, using a novel method, measured the duration of these x-ray pulses. The method uses a portion of the original laser pulse that created the x-ray pulse like a fast shutter to gate the intensity of different parts of the x-ray pulse profile. The authors demonstrate pulse durations of around 2.5 fs—certainly the fastest events ever recorded and slightly shorter than the optical period of the generating optical wave. Truly attosecond-domain pulses still remain just out of reach, but the generation and measurement tools demonstrated here bring them another step closer.

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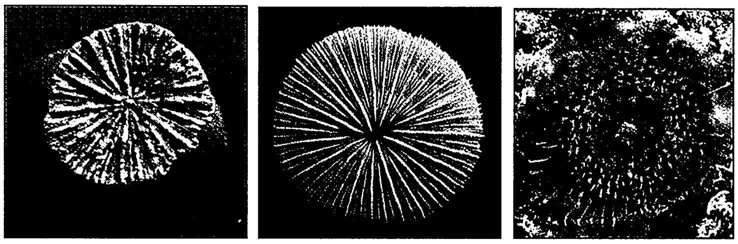
PERSPECTIVES: PALEONTOLOGY AND EVOLUTION

The Origins of Modern Corals

George D. Stanley Jr. and Daphne G. Fautin



Searching for the ancestors. (Left) A fossil scleractinian coral of Triassic age. **(Middle)** The calcified skeleton of a modern scleractinian. **(Right)** A living corallimorpharian polyp, a soft-bodied species. Were the ancestors and some descendants of living corals soft-bodied?

CREDIT: RIGHT IMAGE/JOEL ELLIOTT

Corals belonging to the order Scleractinia are the animals primarily responsible for creating the framework of reefs. These marine invertebrates (see the first figure) are important today and in the geologic past because of their prodigious ability to calcify. Massive deposits of calcium carbonate, some holding important hydrocarbon reserves, trace their origin to ancient coral reefs. Modern reefs exert important controls on global climate and the marine environment, especially in the recycling of carbon. Despite a rich fossil record, however, the origin of Scleractinia has remained shrouded in controversy. Recent work suggests that apparent disagreements and ambiguities may be reconciled.

Most calcifying multicellular animals, or metazoans, made their debut about 540 million years ago (Ma) during the Cambrian period, soon after the start of the Paleozoic era, which saw the explosion of life's diversity in the sea. Molecular evidence indicates that most Paleozoic metazoans originated much earlier, in the Precambrian (*1*). Scleractinians are relative latecomers, appearing in the fossil record during the Triassic period about 237 Ma (see the second figure) (*2*–*4*)—14 million years after Earth's most devastating mass extinction at the close of the Permian period. Not reef-builders at first (*5*), Middle Triassic scleractinians belong to nine or ten families in at least three suborders. This early diversity implies a history unrecognized or unrecorded in the fossil record.

The absence of coral fossils in the first 14 million years of the Triassic coincides with a time when carbonate deposition was suppressed globally (*5*), long after most marine life had been extinguished at the end of the Permian (*6*). This gap is one stumbling block to the old theory that scleractinians were derived from Paleozoic corals. It has been postulated that some survived but that post-extinction abundances were so low, and the resulting fossils so rare, as to elude detection. Another theory is that they survived the 14-million-year gap in as-yet-undiscovered refugia. Both ideas seem tenuous in light of the intense global scrutiny of Lower Triassic rocks.

Moreover, the Paleozoic corals most often proposed as scleractinian ancestors, members of order Rugosa (see the second figure), differ morphologically from scler-

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G. D. Stanley is at the Department of Geology, University of Montana, Missoula, MT 59812, USA. E-mail: fossil@selway.umt.edu D. G. Fautin is at the Department of Ecology and Evolutionary Biology, Natural History Museum and Biodiversity Research Center, University of Kansas, Lawrence, KS 66045, USA. E-mail: fautin@ukans.edu