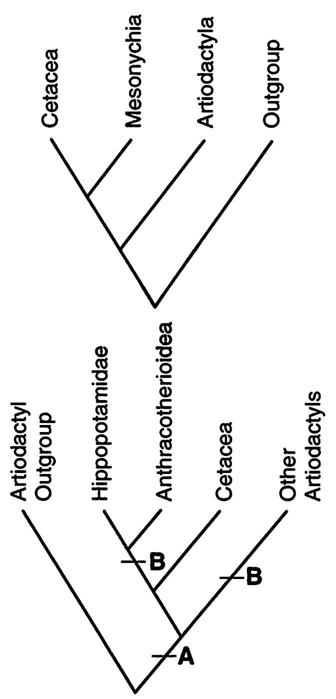
known Eocene artiodactyls (*8*, *10*, *11*). Loss of these features was long considered diagnostic of Artiodactyla. Some of them could represent character reversals or independent losses, but taken together they suggest very early divergence of cetaceans from artiodactyls.

Despite this evidence that cetaceans evolved from artiodactyls, substantial discrepancies remain. If cetaceans belong to artiodactyls, then similarities in the cranial and dental morphologies of mesonychians and cetaceans (*2*, *3*) must be a result of convergent evolution or must have been lost in artiodactyls. Furthermore, molecular data favor a sister-group relationship between whales and hippopotami (*5*). This conflicts with the conventional view based on morphology that hippopotami are closer to other artiodactyls than they are to whales (*12*).

Can a special affinity between whales and hippopotami be reconciled with the fossil record? The existing evidence suggests that cetaceans branched very early from artiodactyls, emerging from an unknown basal artiodactyl that had a slightly more primitive ankle than any known artiodactyl, including *Diacodexis* (the oldest artiodactyl) and anthracotherioids. The latter may be ancestral to hippopotami (*13*, *14*).



Whales and their relations. (Top) Current hypothesis of relationships based on morphology (*3*, *4*). **(Bottom)** Possible relationships compatible with fossil and molecular data, based on the new fossil data (*6*). A, ankle specializations of ancient whales and artiodactyls; B, other artiodactyl specializations.

It is thus conceivable that hippopotami and cetaceans are the only living members of a clade that has been separate from other artiodactyls since before the Eocene (see the second figure). Such a scenario implies that some advanced artiodactyl features evolved more than once: in the anthracotherioid-hippopotamid clade (after the cetaceans diverged) and independently in other artiodactyls.

We are rapidly filling the gaps in the cetacean transition from land to water. Also this week, Thewissen *et al.* (*15*) report slightly older whales from Pakistan that have ankle bones similar to those illustrated here, providing further evidence that this ankle morphology, shared with artiodactyls, was primitive for whales. Two other evolutionary transitions vital to our understanding of the relationship between whales and artiodactyls beg for elucidation: the precise ancestry of hippopotami and the origin of artiodactyls themselves. The answers seem likely to come only from an improved fossil record—perhaps from the same region that has yielded fossils showing that whales evolved from artiodactyls.

References and Notes

1. J. G. M. Thewissen, S. I. Madar, S. T. Hussain, *Cour. Fourschungsinst. Senckenb.* **191**, 1 (1996).
2. M. A. O'Leary, J. H. Geisler, *Syst. Biol.* **48**, 455 (1999).
3. Z. Luo, P. D. Gingerich, *Univ. Mich. Pap. Paleontol.* **31**, 1 (1999).
4. M. C. Milinkovitch, M. Bérubé, P. J. Palsbøll, in *The Emergence of Whales*, J. G. M. Thewissen, Ed. (Plenum, New York, 1998), pp. 113–131.
5. J. E. Gatesy, M. C. Milinkovitch, V. G. Waddell, M. J. Stanhope, *Syst. Biol.* **48**, 16 (1999).
6. P. D. Gingerich *et al.*, *Science* **293**, 2239 (2001).
7. J. G. M. Thewissen, S. I. Madar, *Syst. Biol.* **48**, 21 (1999).
8. J. G. M. Thewissen, S. T. Hussain, *Anat. Histol. Embryol.* **19**, 37 (1990).
9. W. B. Scott, *Trans. Am. Philos. Soc.* **28**, 363 (1940).
10. K. D. Rose, *J. Paleontol.* **59**, 1203 (1985).
11. J. Erfurt, *Hallesches Jahrb. Geowiss. B* **12**, 57 (2000).
12. M. C. McKenna, S. K. Bell, *Classification of Mammals Above the Species Level* (Columbia Univ. Press, New York, 1997).
13. E. H. Colbert, *Am. Mus. Novitates* **799**, 1 (1935).
14. W. P. Coombs Jr., M. C. Coombs, *Neues Jahrb. Geol. Palaeontol. Monatsh.* **1977** 584 (1977).
15. J. G. M. Thewissen *et al.*, *Nature* **413**, 277 (2001).

16. I thank P. D. Gingerich for providing casts of the new fossils, E. Kasmer for preparing the first figure, and J. Mussell and S. Zack for helpful discussion.

PERSPECTIVES: APPLIED PHYSICS

Optics in the Nano-World

S. W. Koch and A. Knorr

Applications of optical microscopy are generally limited by the standard resolution limit set by the wavelength of visible light. The invention of near-field scanning optical microscopy (NSOM) first enabled this limit to be overcome, opening up many systems, from physics to biology, to investigation by optical microscopy. NSOM offered greatly improved spatial resolution compared with conventional optical microscopy, and the use of tunable excitation sources allowed basic spectroscopic information to be obtained. On page 2224 of this issue, Guest *et al.* (*1*) report the next major step forward in this field. The authors describe a technique that combines the high spatial resolution of NSOM with the high spectral resolution of coherent nonlinear optical spectroscopy.

Optical measurements at the nanometer scale require a light source with an illumination spot in the nanometer range. For visible-light frequencies, where the wavelength is a few hundred nanometers, conventional optical microscopy fails because the resolution is restricted to half the wavelength of the used light (*2*). To overcome this problem, the light must be localized in a spot with a diameter much smaller than the wavelength of the light. Ideally, the spot should have nanometer-scale dimensions. This can be done by applying small apertures (*3*).

The price for this high resolution is that the character of the light changes drastically when it propagates through the aperture. The localization of the light waves results in the formation of evanescent waves, which have an imaginary wave number and decay exponentially in space (in contrast to conventional light waves, which propagate freely). The intensity of an evanescent wave thus decays rapidly as the distance from the aperture increases. Therefore, the aperture has to be close to the object, often only a fraction of the wavelength away. This is the regime of near-field optics.

NSOM techniques have many applications in solid state physics, where substantial efforts are made to design electronic devices with features on the nanometer scale. Electrons can be confined in nanometer-scale structures, called quantum dots (*4*). In these structures, the matter-wave properties of the electrons are changed drastically because the spatial confinement of the electrons approaches the deBroglie wavelength. Their electronic and optical properties therefore differ qualitatively from those of the bulk material.

The atomic landscape encountered by electrons in a quantum dot can be mapped and analyzed with tunneling spectroscopy

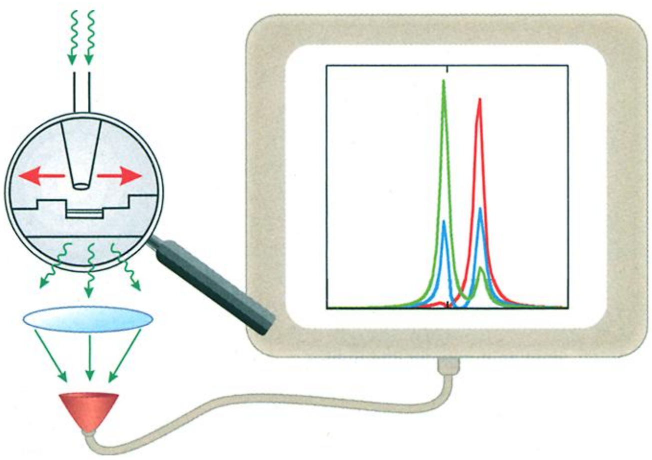
S. W. Koch is in the Department of Physics, Philipps University, 35032 Marburg, Germany. E-mail: stephan.w.koch@physik.uni-marburg.de A. Knorr is at the Institute for Theoretical Physics, Technical University, 10623 Berlin, Germany. E-mail: andreas.knorr@physik.tu-berlin.de

(5). Optical transitions between electronic states in a quantum dot are much harder to map and address with current techniques. Optical addressing of individual electronic quantum states localized on a quantum dot is a particularly challenging task.

To excite a single electronic quantum state, the light source must overlap in space with this state. However, spatial overlap is not sufficient because several states often coexist in a given structure. The incident light must therefore also overlap spectrally with the quantum state. Fortunately, these states are different in energy and can therefore be excited selectively by changing the frequency of the incident light—but only if the spatial resolution is high enough to resolve single quantum dots and the spectral resolution is sufficient to resolve the line width of a single optical transition.

Guest *et al.* have now succeeded in exciting and detecting single optical transitions on a nanometer scale in a solid material. In their experiment, spectrally and spatially well-resolved laser pulses are used to generate electronic excitations in quantum dots defined by thickness fluctuations of a GaAs semiconductor film. The nanometer-scale light source is obtained by the propagation of conventional laser light through an aluminum-coated fiber tip.

The measurements yield the dipole strength, decay times of the emission, and lifetimes of the electronic excitation as the probe is scanned over the film. These results are obtained using the nonlinear interaction of two incident light waves in the semiconductor. The nonlinear optical response leads to wave mixing between the incident waves, which can be detected in the frequency domain. The experiment combines subwavelength spatial resolution with an energy resolution in the nano-electron volt range, enabling single electronic states in the quantum dot to be addressed. By detecting the light behind the sample (see the figure), the authors show that single quantum states localized on a nanometer scale and their optical properties can be detected over an array of several micrometers.



Optical near-field spectroscopy. The light of one or more light sources (lasers) is coupled into an optical fiber with a tapered, metal-coated tip. The evanescent field of the fiber tip acts as local excitation source that is scanned over the structure under investigation (magnified in the figure). The transmitted light is collected and processed to yield optical spectra. The spectral information depends on the exact position of the excitation source (different curves on the display) and on the frequency of the laser sources.

When light excites an optical transition, the material excitation has the same phase and angular momentum as the light source. This quantum coherence decays, sometimes very fast, due to interactions with other excitations and vibrations in the material. Guest *et al.*'s technique enables them to map dynamical information associated with the excitation decay of single quantum dots and to determine the decay of optical polarization (dephasing) due to loss of quantum coherence. The work also points the way to the next inevitable advance: the development of nonlocal spectroscopy, which may be based on two NSOM probes and should enable the detection and characterization, for example, of transport of quantum coherence.

Optical techniques such as that reported by Guest *et al.* will allow us to resolve spatial properties on small scales, complementing the progress achieved by ultrafast-pulse optics in the time domain. These high temporal and spatial resolution techniques will facilitate the investigation of quantum mechanical questions concerning excitations in a complex solid state environment such as a quantum dot immersed in a semiconductor film. This work will not be restricted to pure research but may even lead to the development of a wide range of practical diagnostic tools and device applications.

References and Notes

1. J. R. Guest *et al.*, *Science* **293**, 2224 (2001).
2. Lord Rayleigh, *Philos. Mag.* **8**, 261 (1879).
3. M. A. Paesler, P. Moyer, *Near-Field Optics: Theory, Instrumentation, and Applications* (Wiley, New York, 1996).
4. L. Banyai, S. W. Koch, *Semiconductor Quantum Dots* (World Scientific, Singapore, 1993).
5. D. A. Bonnell, Ed., *Scanning Probe Microscopy and Spectroscopy: Theory, Techniques, and Applications* (Wiley, New York, 2000).

PERSPECTIVES: ATMOSPHERIC SCIENCE

Bridging the Atmospheric Divide

Martin J. Jarvis

One of the least explored regions of Earth's atmosphere is finally emerging from obscurity. The mesosphere and lower thermosphere (MLT), between 50 and 150 km altitude (see the first figure), has long suffered from its inaccessibility to the highest research balloons and the lowest orbiting satellites. Several international initiatives now aim to plug this knowledge gap.

The new initiatives take advantage of recent technological developments to study the MLT from the ground and from space. They are particularly timely because of the growing realization that the MLT is an important link in the vertical transfer of energy and material in the atmosphere, that mesospheric phenomena may be the most sensitive indicator of global temperature change, and that this region is becoming increasingly relevant to aerospace technology (*1*).

In summer, the polar mesopause, which defines the boundary between the mesosphere and the thermosphere, is the coldest place anywhere in Earth's atmosphere. At 130 K, it is some 70 K colder than would be expected under simple radiative equilibrium. The cooling is driven by gravity waves, which can be caused by the impact of weather on mountain ranges or by shear in the atmosphere. Gravity waves propagate upward from the troposphere and break in the mesosphere.

A slightly warmer summer mesopause is expected in the Antarctic than in the Arctic because the different land-ocean configuration in the Antarctic leads to a weaker

The author is at the British Antarctic Survey, Cambridge CB3 0ET, UK. E-mail: mjja@bas.ac.uk