Let there be fluid light

There is in nature — at least on Earth, that part of nature we know so well — a tendency for complexity to grow through time. The kinds of things that exist on our planet do not remain constant in number. New species emerge from old, and our technology also marches ever onwards, creating new materials and eliciting new phenomena, always expanding into the world of, as some now say, the “adjacent possible”.

The more we learn and understand, the more we learn how to create phenomena we do not understand — even some that have never existed anywhere in the Universe. Take light, for example.

In classical electrodynamics, light in a vacuum follows a linear wave equation; hence, two beams of light can cross paths without disruption. In quantum language, photons do not interact. In fact, this isn’t quite true in a full quantum treatment of electrodynamics: photons in a vacuum, as Heisenberg and Euler showed in 1936, should interact very weakly through a secondary mechanism linked to the creation of virtual pairs of electrons and positrons. Experiments with intense lasers may see this effect within a few years.

But here’s a theorem of human behaviour. If something is barely possible, you can trust in the inquiring human mind to make it more possible over time. Sure enough, over the past few decades, the idea of inducing photons to interact more strongly has gone from fantasy to reality, and experiments now routinely produce relatively dense quantum fluids in which photons move, yet interact, to create rich collective motion and dynamics (an excellent review by Iacopo Carusotto and Cristiano Ciuti has just appeared in *Reviews of Modern Physics* **85,** 299–366; 2013).

The basic strategy for getting photons to interact is to somehow ‘dress them up’ so they look and behave a little differently. One way is to choose a suitable medium so that a photon, as it passes through, changes that medium slightly, altering its index of refraction or some other property, and thereby influencing any other photon that passes. Another is to engineer a medium in which a photon isn’t ‘just’ a photon — an excitation of pure light — but instead must involve other degrees of freedom, electronic or otherwise, which then mediate an indirect interaction between the photons. Both techniques stir up weird and fascinating physics.

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Twenty years ago, for example, pioneering research exploited the nonlinear refractive properties of certain crystals to bring to life the direct analogy of fluid vortices in light flow. In a photon fluid, the role of the fluid velocity is played by the gradient of the phase of the photon wavefunction, and the intensity of the field corresponds to the photon density. Hence, in these experiments, the vortex appeared as a phase singularity forming the core of a helical wavefront travelling through the crystal.

In classical fluids, of course, vortices will tend to drift under the hydrodynamical equivalent of the Magnus force — the force that makes spinning balls or other projectiles curve in the direction of their spin. This has also been seen in photon fluids. Going further, experiments in nonlinear optical media have also explored collisions between solitons — the close analogy to stable, persisting nonlinear hydrodynamic waves — as well as the creation and behaviour of shock waves. One recent experiment followed a photon fluid passing through a small barrier potential, and another looked at the Rayleigh–Taylor instability in a stratified photon fluid.

To bring home the generality of such behaviour, closely related phenomena have also been explored in the very different setting of semiconductors. In suitably designed planar microcavities, a photon in the cavity isn’t just a photon but a ‘polariton’ — a photon dressed by a matter excitation (in this case an ‘exciton’, that is, an electron–hole pair bound by their interaction). Two such photons (polaritons) then interact because their associated matter excitations interact. Experiments in these systems over past decades have observed a variety of fluid phenomena, including the propagation of sound waves and the hydrodynamic nucleation of vortex–antivortex pairs for a fluid passing by a defect (G. Nardin *et al. Nature Phys.* **7,** 635–641; 2011).

All these experiments, however, still achieved only weak photon interactions — sufficient to see fluid-like behaviour, but not enough to elicit the more complex dynamics possible with strong interactions. The analogy is closer to a dilute gas than to a dense fluid. But recently developed techniques make photons interact much more strongly, again by exploiting the delicate interactions of light with matter.

Fifteen years ago, theorists first noted that the optical nonlinearity of a cavity could in principle be high enough that the presence of a single photon would so detune the cavity that another could not enter. This creates a so-called photon blockade — an effective complete repulsion between photons. Experiments realized the effect within the next decade. Now imagine that you construct a tight array of such cavities, close enough together so that the wavefunction of a photon in one bleeds out into neighbouring cavities. This makes it possible for a photon to hop from one cell to another, but only to cells that are unoccupied.

The result — in principle, at least — is a photon fluid with very strong interactions. In this system, it should be possible to see photons doing things we’re only used to atoms doing, such as undergoing a transition from superfluid to a so-called Mott insulator, in which flow is completely suppressed by interparticle repulsion. This hasn’t been done experimentally yet, but achievement is probably close in a number of different array technologies.

The lesson is that light, as we know it historically, is just light only under certain conditions. Change the context, and light may turn out to be a very different thing. In this sense, physics isn’t just discovered, but created and invented; we are co-creators with nature.

Perhaps we will ultimately learn that this is true not only of light, but more generally. If you believe, as some do, that all the laws of physics are ultimately emergent phenomena, then even what we today call the fundamental laws might one day be subject to re-engineering, if we can only learn to control the right contextual variables. ❐

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Correction

In the Thesis 'Let there be fluid light' (M. Buchanan, *Nature Phys.* **9,** 260; 2013), the name of the co-author of the review cited in paragraph four was misspelt, it should have read Cristiano Ciuti. Corrected in the HTML and PDF versions.