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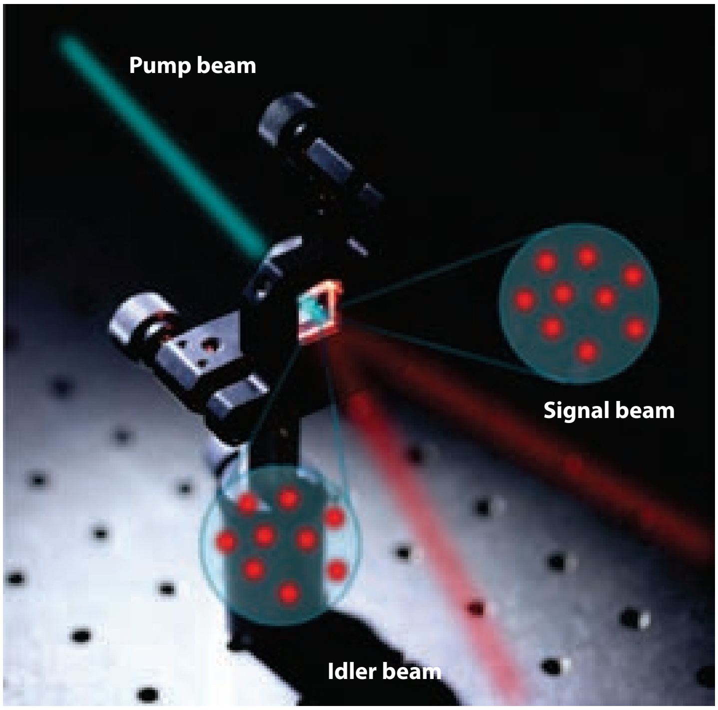
Traditional imaging systems rely upon light transmitted by or scattered from an object to form an image on photographic film or a detector array. But in another kind of system, "ghost" imaging, the image is formed from light that has never interacted with the object. This counterintuitive result led to widespread interest in early quantum ghost-imaging approaches during the late 1990s. Since then, the field's evolution has provided even more surprises. In this feature, we look at some of those surprises, and survey recent progress in both quantum and classical/computational ghost imaging.

Logging the camera data over many photon pairs, and summing the corresponding frames, enables the "ghost" image to emerge, photon by photon.



Spontaneous parametric down-conversion

In spontaneous parametric down-conversion (SPDC), a high-energy pump photon is converted into two lower-energy signal and idler photons. Conservation laws mean that these down-converted photons are highly correlated in spatial degrees of freedom.

Quantum: Imaging via entanglement

Ghost-imaging systems rely upon spatial correlations between two separated optical fields. Quantum ghost imaging uses correlations between entangled photons, which are often generated through spontaneous parametric down-conversion (SPDC). In SPDC, a single photon from a pump laser, passed through a nonlinear crystal, is converted into two new photons, termed signal and idler photons.

Energy conservation requires that the sum of the frequencies of the signal and idler photons equals the pump frequency—and, upon close examination, that the two photons be highly position-correlated within the diameter of the pump beam. This position correlation means that, in all subsequent image planes of the crystal, the position of the signal and idler photons within any given entangled pair are nearly identical, yet the pairs are themselves randomly distributed over the field of view. (The strength of these correlations depends on the crystal length; for a crystal only a few millimeters in length, the spatial correlation for near-visible-wavelength photons is at the sub-micron level.)

To create an imaging system, the signal and idler photons are separated into distinct optical paths (using, for example, a polarizing beam splitter). Along one path (the signal path), the crystal plane is imaged onto the plane of a detector array, such as a single-photon detector array or a camera. Along the other path (the idler path), the crystal plane is imaged onto the plane of an unknown object. Beyond the object plane is a single-element (that is, single-pixel) detector, large enough in diameter to collect all the photons emanating from any point within the area of the pump beam.

Once detected, the precise position of the photon is inherently unknown, as a single-element detector lacks any spatial resolution. However, the position information is not lost: for every (idler) photon transmitted through the object, the camera located in the other path of the ghost-imaging system records the precise position of a position-correlated (signal) partner

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photon. The data capture process retains only the camera-detected photons for which the partner photon was detected by the single-pixel detector; logging the camera data over many photon pairs, and summing the corresponding frames, enables the "ghost" image to emerge, photon by photon.

Building a better camera

The ghost-imaging system, as described above, relies on the camera being able to locate a single photon within its entire field of view, and to distinguish that photon from any dark noise or readout noise. Early ghost-imaging pioneers, lacking so sensitive a camera, used a scanning small-element single-photon detector. Because such detectors examine only an image pixel at a time, most photons go undetected, and the system's detection efficiency can never exceed the reciprocal of the number of image pixels.

Our group's contribution to quantum ghost imaging has been to eliminate the need for scanning by using a camera that can perform unambiguous single-photon detection events across its entire field of view. While electron-multiplying CCD cameras have high quantum efficiency, they also accumulate readout noise, such that, for a single frame, the single photon is indistinguishable from hundreds of other events associated with the readout process. Instead, we use an intensified CCD (ICCD), which can be time gated, such that it is actively collecting data only for a few nanoseconds and can be triggered at hundreds of kHz.

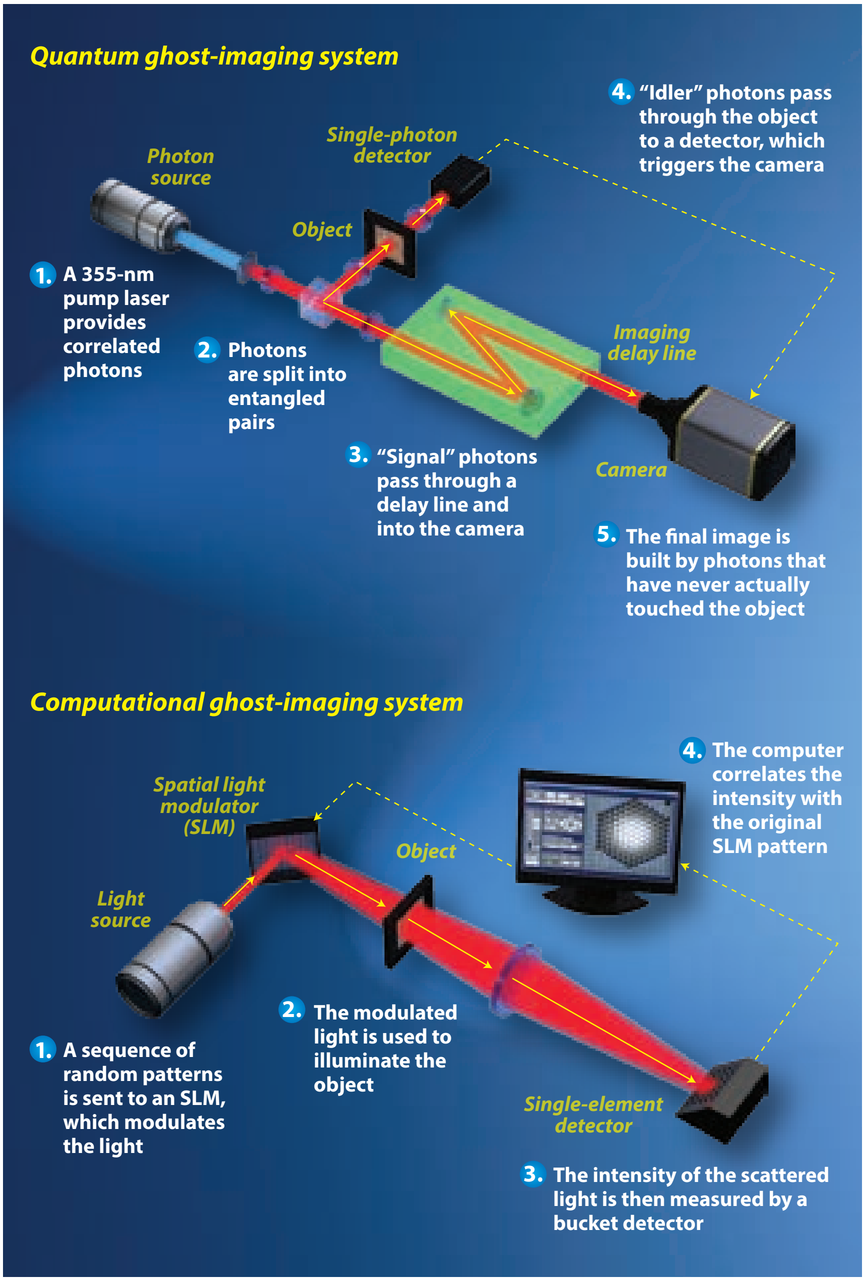

Illustration by Phil Saunders

Within this short time window, thermal noise is unlikely to lead to any false detection event. However, the time gating can be synchronized to yield good probability of a single photon arriving within the same time window, yielding a valid detection event. In this way, the single photon can be position-detected against a noise-free background.

Given the stochastic nature of the SPDC process, the photon arrival is a randomly timed event, and so without properly adjusted time gating the photon would, in all likelihood, arrive outside of the active time window of the camera. The key to our experiments' selectivity is that in SPDC, in addition to the strong spatial correlation, the two photons are also highly time correlated. Hence, providing that delays associated with propagation

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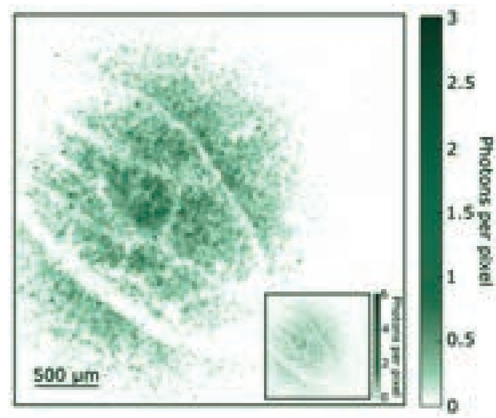


Optimized low-light imaging

Optimized low-light image of a wasp wing, with the original data inset. The original data contain 48,000 photons in the 600×600-pixel image area, or an average of 0.13 detected photons per pixel.

distances are taken into account, a detection by the single-element detector can be used to send a perfectly timed signal to trigger the ICCD.

Experimentally, such synchronization has its challenges. The finite speed of an electrical signal along any connecting wire means an unavoidable delay between the camera trigger and the detection. Moreover, the finite response time of the intensifier dictates that it takes tens of nanoseconds to activate the camera once it is triggered. We overcome both problems by delaying the arrival of correlated signal photons at the camera, using an image-preserving optical delay line, typically 20 m long.

> Nothing in quantum ghost imaging requires quantum entanglement—only position correlation between photon pairs.

One photon (or less) per pixel

Thus configured, our ghost-imaging system can acquire images of real objects, where the image is formed from the summation of a remarkably small number of individual photons. The final images typically contain on the order of one photon per image pixel. This small number of photons in any individual pixel does mean that the noise inherent in the counting statistics leads to a noisy raw image. However, images of real objects are not collections of random pixel values; rather, adjacent pixels tend to have similar values, a fact that is the basis of image compression algorithms such as JPEG.

The same compression principles can be applied to reconstruct image estimates from photon-sparse data. By assuming a Poisson distribution of the expected number of photons within a given image pixel, and combining this with a metric for pixel-to-pixel correlations, one can define a cost function that can be applied to any postulated image. Optimizing that cost function provides an image estimate that is an appropriate compromise between the raw (but noisy) data and the constraints typical of real images. This approach can reconstruct images derived from photon numbers corresponding to an average of less than one photon per image pixel—an achievement that may be critically important for a number of applications.

Also of importance for specific applications is that the signal and idler photons need not be of the same frequency: SPDC requires only that the *sum* of the two photon frequencies equal that of the pump. Indeed, modifying the phase-matching conditions within the crystal can result in a large difference between the signal and idler frequencies. One recent experiment used an optimal 1.5-μm idler photon wavelength to probe the transmission of a silicon wafer, while the image information was recorded using a signal wavelength at 460 nm, ideally suited to the peak wavelength performance of the ICCD camera.

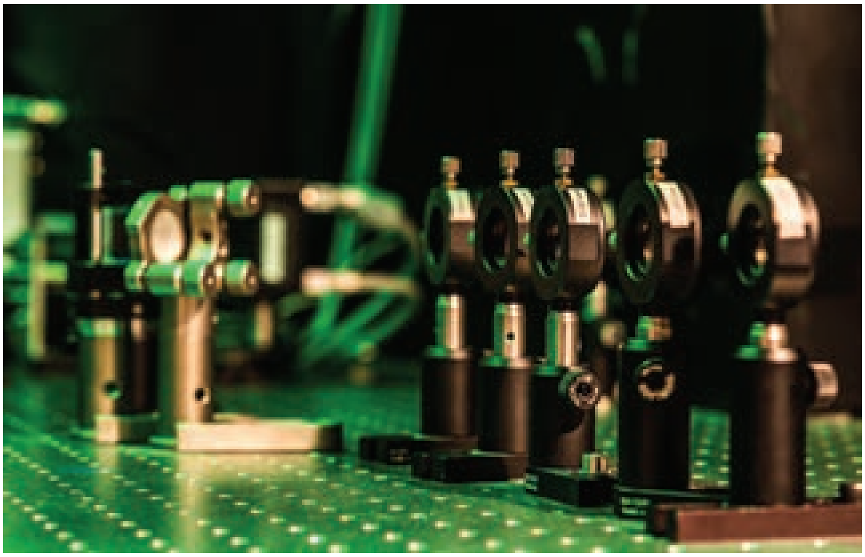
Finally, it is worth noting that nothing in quantum ghost imaging requires quantum entanglement—only position correlation between photon pairs. Moreover, while the introductory system we described was configured such that the crystal plane was imaged onto both the object and the camera, a ghost-imaging system in which both the object and the camera are positioned in the far field of the crystal is quite feasible. Including appropriately interchangeable lenses after the crystal allows the crystal to be switched between the image and far-field planes. In this case, the system relies upon the anti-correlation in transverse momenta of the signal and idler photons, which results in an anti-correlation in their transverse positions in the far field.

The principles associated with such a far-field system are similar to those described for the image-plane system, except that this anti-correlation results in an inversion of the image with respect to the object. The resulting upright or inverted images are manifestations of an EPR-type position-momentum entanglement between the signal and idler photons.

Classical: Paired photons not required

Correlations between data collected along two paths are what make ghost imaging possible. And those correlations need not be between individual photon pairs: classical light fields can also show spatial correlation.

For example, if a field consisting of a random optical pattern containing many photons is incident upon a 50-50 beam splitter, then within the limits of the Poisson statistics of photon



Part of an imaging delay line used in a quantum ghost imaging system. This delays the arrival of correlated signal photons at the camera to account for the delay of the electrical trigger signal.

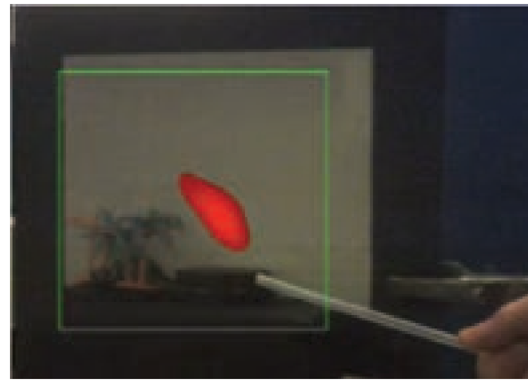
Photo by Kevin J. Mitchell

From ghost imaging to ghost diffraction

Although quantum ghost imaging can be analyzed abstractly in terms of nonlocal correlations associated with a two-photon wavefunction, a more visual conceptual model was proposed in 1996 by T.B. Pittman and colleagues: back-projection. This model uses the fact that the images that result from ghost imaging are *equivalent* to those that would result from replacing the single-element detector by a light source, from which the emitted signal back-propagates through the object to the crystal—which, in this model, acts as a mirror to reflect the light to the camera.

Since the object is imaged to the crystal/mirror and the crystal/mirror is itself imaged to the camera, the back-projection model merely describes a conventional imaging system of the sort most optics researchers are comfortable thinking about. Such models allow us to quickly predict what might happen if we were to reconfigure the system by moving the camera into the far field, where the image of the object would, in a classical imaging system, be replaced by its diffraction pattern. In fact, this reconfiguration does convert a ghost-imaging system into a ghost-diffraction system.

Thus, use of the back-propagation model to make an analogy to a conventional imaging system allows useful insights into configuration options for additional experiments. For classical imaging systems, we know that one only obtains a high-contrast interference pattern if, in addition to moving the camera into the far field, the light source used is spatially coherent. Thus ghost diffraction requires that the single-element detector be spatially filtered so that it detects only a single spatial mode (which is conveniently achieved by coupling the detector through a single-mode optical fiber).



Single-pixel camera imaging

A single-pixel camera (left) provides an image of methane gas (flow rate ≈ 0.5 liters/min) recorded at ≈1.65 µm, superimposed with a full-color navigation image.

number variations, two identical optical patterns result, coupled into different paths. One of these paths can be imaged to a camera, and the other imaged to the object, through which the amount of transmitted light can be measured using a single-element detector.

Rather than measuring individual photons, the single-element detector now measures an analog intensity level, the magnitude of which measures the overlap integral between the random optical pattern and the transparent bits of the object. As the random pattern changes, this analog level goes up and down, depending upon the resulting overlap integral. If the random patterns are recorded by the camera and summed together, the result is a near uniform image. If, however, the individual patterns are weighted by the analog intensity level, the resulting weighted sum acquires features corresponding to an image of the object.

> Conceptually, computational ghost-imaging systems are closely related to so-called single-pixel cameras.

Again, it is important to note that the camera signal is obtained from light that has never interacted with the object. This classical form of ghost imaging has many of the features of the quantum version, but the image information is now superimposed on top of a large yet uniform background that needs to be numerically subtracted from the data.

Computational: Using a known pattern

One key to a classical ghost-imaging system is a mechanism for generating ever-changing random optical patterns. Scattering laser light through turbid media offers one option; another is to use a programmable spatial light modulator (SLM), such as those found in data projectors of the sort used for presentations.

Ingeniously, if the pattern is created in this way, then the classical ghost-imaging system becomes much simpler: Because the patterns of light used are now produced deterministically from a computer program, they are fully known, and neither the camera nor the beam splitter are needed to extract that spatial information. So the object may be directly illuminated by each known pattern, for which the single-element detector measures the light transmitted (or, indeed, backscattered) by the object.

In this case, the spatial correlations, rather than being between two optical fields, are now between the photodiode signal and the pattern in computer memory. As a result, the technique is called computational ghost imaging. (In the original proposal, both the intensity and phase of the light were known, such that the plane of the modulator did not need to be imaged onto the object; rather, the intensity distribution at the object could be calculated.) In its simplest form, a computational ghost-imaging system can be based on a conventional data projector and a single photodiode to measure the backscattered light. Extending the system to incorporate multiple photodiodes provides the option of hyperspectral imaging, polarization imaging, or even, through a photometric technique, 3-D imaging.

Conceptually, computational ghost-imaging systems are closely related to so-called single-pixel cameras. In both cases, the imaging system combines a single-pixel detector, an illumination source and an SLM, the plane of which is imaged to the object. In computational ghost imaging, the light source is patterned by the SLM and used to illuminate the object, with the single-element detector measuring the backscattered light. In a single-pixel camera, the object is illuminated and the pattern of scattered light is imaged onto the SLM, the total transmission through which is measured using the single-pixel detector. In both cases, the patterns and resulting signals are the same, as are the algorithms required to reconstruct the images.

In both a computational ghost-imaging system and a single-pixel camera, control over the precise patterns used means that, rather than using a series of random patterns, it is possible to optimize the pattern set, to make the patterns perfectly orthogonal and provide the best sample for the likely image type and resulting correlations. Such techniques lead to image reconstructions from comparatively small sets of patterns, for which the number of measurements required is many fewer than the number of pixels in the resulting image—a form of compressed sensing.

New imaging horizons?

While single-pixel imaging is clever in itself, what advantages might it hold over using a standard detector array, positioned in the focal plane of a camera? One possible advantage is that detector arrays have wavelength ranges restricted by material type—for example, silicon-based detectors work only in a 200-to-1100-nm spectral window. By contrast, data projectors can be configured to work across wider wavelength ranges. And, instead of large detector arrays, all that is needed is a single-element photodetector with sensitivity at the chosen wavelength. This is perhaps most useful in the shortwave infrared, allowing low-cost imaging systems to be constructed for imaging at 1 to 2 μm. This allows, for example, the direct imaging of methane gas (see figure at left).

In summary, in both its quantum and classical forms, we believe that ghost imaging has relevance to physicists interested in demonstrating the "spookiness" of quantum mechanics. But it also could help computer scientists developing new image-processing techniques for extracting maximum information from compressed-sensing techniques, and engineers building new systems capable at imaging at unusual wavelengths. OPN

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