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How a thirty-year-old quantum tale of two photons became ghost imaging

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The term Ghost Imaging embeds the notion that images can be formed by photons that have not interacted directly with an object. The first demonstration of ghost imaging turns 30, and the rich physics contained therein remains inspiring, fuelling advances in computational imaging with classical light, and novel imaging modalities with quantum light.

In November 1995 under the guidance of Prof. Yanhau Shih, Todd Pittman and co-authors reported[1] on a novel optical imaging method that used two entangled photons as a resource. In their experiment, each of the two entangled photons was sent to a different branch. The first photon travelled through the "object arm", containing the object to be imaged (the letters "UMBC" of their institute) and ending with a bucket detector with no spatial resolution. The second photon, instead, travelled through the "imaging arm", an empty branch ending with a spatially resolved detector. Neither photon by itself had enough information to construct the image of the object: the photon going through the object arm lacked spatial resolution due to the detector, while the other photon did not directly see the object. The first rash conclusion that comes to mind is that this setup would be a very inefficient imaging setup.

Defying this initial belief, an image of the object could be seen when both photons were measured in coincidence, as if the photon that never interacted with the object (in the imaging arm) had somehow "seen" it. While the work was relying on an imaging setup, its purpose was not directed towards imaging at all. Instead, it was aimed at joining the debate on whether photons could only interfere with themselves, as mooted by Dirac (a topic the authors continued to pursue in the years that followed—see Box 1). Yet it is in imaging in which this work made its mark as the first demonstration of "Ghost Imaging", a term coined by Prof. C.N. Yang (the 1957 Nobel Laureate) and now universally accepted[2].

Box 1

Reflections by the authors

According to Prof. Yanhua Shih, author of ref. 1, the motivation for the experiment started from a debate:

The community believed that Dirac was mistaken to say that "a photon only interferes with itself. Interference between two different photons never occurs." This view was based on the observation of an anti-correlation, now called the HOM dip, in which the signal photon and the idler photon must "meet" and "interfere" with each other at a beamsplitter. We believed Dirac was correct. The nonlocal anti-correlation and correlation we observed are the results of a two-photon interference phenomenon: a pair of photons interferes with the pair itself. In Dirac's language: "A pair of photons only interferes with the pair itself, interference between two different pairs never occurs." Even today, we can still find statements like "when the two photons meet and interfere at a beamsplitter …" in journal or internet publications. We decided to defend Dirac, the standard quantum theory, by starting a "ghost imaging" (Todd Pittman's thesis) and "ghost interference" (Dmitry Strekalov's thesis) experimental investigations simultaneously. In these experiments, the entangled signal photon and idler photon never meet and interfere at a beamsplitter, but we still observe nonlocal anti-correlation ("dark" correlation) and correlation ("bright" correlation). It took us a decade to realise that two-photon interference is not limited to entangled states but can also occur in thermal states. In 2005, we successfully produced two-photon image forming correlation from randomly created and randomly paired photons in thermal state and published our first ghost imaging experiment of thermal light.

Todd Pittman, author of [1] recalls the thrill of the experimental work:

It was such an amazing time - there was a real sense of unknown exploration in the lab, and designing the experiments and getting everything to work was quite an adventure! By today's standards, the experiments seem somewhat straightforward—but back then we had to home-build much of the equipment and try all kinds of dead-end paths until we got it right. There were a lot of "all-nighters" in the lab required to get the results, and seeing the "UMBC" image emerge from the data for the first time was super exciting and very rewarding; I remember it like it was yesterday!

Even in the context of imaging, the work posed another conundrum: the observed image was twice as large as the object, despite the initial intuition suggesting they should be nearly the same size. The answer to this riddle was rooted in "retrospective" thinking. The object photon was imagined to travel backwards (in time!) to the crystal of its birth, passing through the object along the way. This backwards-travelling photon would then bounce off the crystal—as if it were a mirror—travelling forward again, this time following the path of its paired partner photon to the detector. The resulting distances with the lens in the imaging arm exactly accounted for the magnification. This remarkable insight, which we now know as the Klyshko advanced wave analogy to entanglement, has since been used extensively to align, explain and classically mimic quantum experiments. The authors remarked[1] that it might be possible to emulate some features of the experiment with a classical source, a comment that was proven to be prescient in the debates and demonstrations that followed.

In a 30-years span, many advances have been directed to enriching the technology, fundamental physics and applications of the original idea, captured schematically in Fig. 1. In the original setup, a single mode fibre (a single pixel detector) was scanned across the XY plane to form the image.

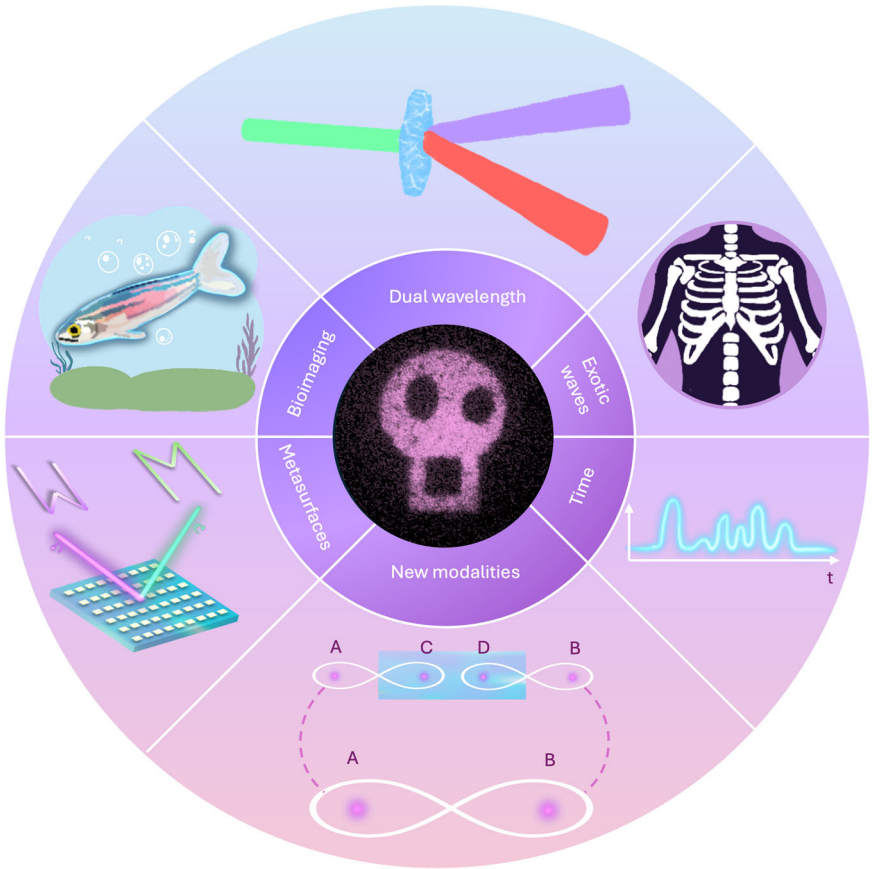

Fig. 1 | Modalities in ghost imaging. Ghost imaging has evolved from early experiments with non-degenerate wavelengths to breakthroughs with hard x-rays, ultrafast reconstruction of temporal structures, and high-resolution imaging of entire biological specimens. Advances in miniaturised metasurfaces have further expanded its capabilities, while emerging techniques like entanglement-swapped GI open new possibilities, including the teleportation of images.

This was later replaced by digital projective masks using common display technology, introducing computational imaging techniques to the acquisition of data, which has in turn accelerated classical single pixel computational imaging[3]. Today, quantum camera technology has matured to the point that single photon coincidences can be measured in real-time with excellent resolution while the digitalisation of data has facilitated the use of artificial intelligence to speed up and enhance the reconstruction of the image[4]. To fully understand the revolutionary potential of the original work[1], it is enough to glimpse at how much the techniques have deviated from the original formulation. The original work demonstrated that photons at the same wavelength, created at the same source, could probe structures in the spatial domain with "pixels". Thirty years later, each of these paradigms has been broken.

Using a non-degenerate ghost imaging set-up, where the two photons have different wavelengths, allows imaging in spectral regions where spatially resolved detectors are either impractical, prohibitively expensive, or limited in resolution[5]. It also raises fundamental questions on magnification and resolution in dual wavelength experiments, revealing that it is primarily the wavelength of the object photon that matters. Remarkably, there is no fundamental limit to how different the photon wavelengths can be, now extended into the infra-red and terahertz regions, particularly valuable for biological applications as these wavelengths can safely penetrate biological matter while remaining non-ionising.

It is also possible to perform ghost imaging with two photons that are initially completely independent, perhaps each from a different entanglement source, that become correlated by entanglement swapping and teleportation. In entanglement-swapped ghost imaging, two pairs of photons, say photons A/B and C/D, are created by independent sources. One photon from each pair (say B and C) is used to ensure the entanglement between the other two to be used for imaging, photon A for the image and photon D for the object. The object information can be said to be teleported from photon D to photon A. The physics returns counterintuitive outcomes[6], for instance, contrast inverted images, that are bright where the object is dark, and dark where the object is bright, a consequence of the symmetry of the quantum state.

It is possible to alter the spatially resolved detector to be modal rather than pixels, both valid approaches to reconstructing spatial information. The holographic digital masks in projective measurements are one such basis, but spatial modes of light are a valid alternative, offering the ability to resolve beyond the diffraction limit in quantum ghost imaging experiments, and leverage off object symmetry to reduce the number of measurements needed[7]. Why restrict to the spatial degree of freedom only? The language of ghost imaging can be reframed by returning to the original experiment: high resolution images were captured by collecting object photons with low resolution detectors. This notion has proven powerful in the time domain too[8], powering the detection of ultrafast processes using two detectors with distinct temporal resolutions: a fast detector that does not directly observe the object, and a slow detector that captures the object but is too slow to resolve its temporal structure. The advantage of ghost imaging becomes further evident by negating unwanted dispersive effects, e.g., when information is transmitted through a multimode fibre. It has facilitated exciting advances when mixed with non-optical frequencies, e.g., acoustic waves,

while the ability to extract an image from statistical correlations, even in high-noise settings, hints at powerful applications in sonar, biomedical ultrasound, and non-destructive testing.

These conceptual and technological leaps have seen ghost imaging used in a variety of applications. It is well known that optical imaging is crucial in the study of biological systems, allowing the visualisation of cellular structures and dynamic processes. Unlike classical imaging that requires intense illumination, quantum ghost imaging offers a promising alternative with low photon fluxes, less than a photon per pixel. This can be leveraged further by adding in extra degrees of freedom, such as polarisation, to extract additional information from objects. This, for instance, has allowed the reconstruction of both spatial and birefringent properties of entire biological samples, demonstrated[9] on a zebrafish and a mouse brain. While quantum imaging in general has lagged behind its classical counterparts in terms of image quality and resolution, the recent advances in adaptive correction have shown promise to bring them on par[10]. We expect to see rapid progress in such applications with the convergence of our modern ghost imaging toolkit.

To conclude, three decades have not been enough to quench the excitement in ghost imaging. The impact of the original experiment goes far beyond its original intent, unintentionally catalysing new forms of classical and quantum imaging, indirectly launching the field of computational imaging, and more recently extended beyond photons to sound and matter. Prof. Miles Padgett (FRS) of the U. Glasgow puts it aptly, "This paper opened our eyes to the quantum application of multi-modal spatial correlations. The privilege of 20/20 hindsight suggests some of their results could be mimicked using classical correlations, but this realisation fuelled research in computational imaging. An amazing paper inspiring work in both quantum and classical imaging." We watch with interest to see what the next generation of scientists do with this inspiring platform.

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Author contributions

A.F., F.N. wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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