

# Social Quantum Science

*Researchers in a lab at Aarhus University have developed a versatile remote gaming interface that allowed external experts as well as hundreds of citizen scientists all over the world to optimize a quantum gas experiment through multiplayer collaboration and in real time. [29]*

*"As crazy as all this looks, there appears to be strong reliability in these behaviors that could even be predictably and practically manipulated," Landman said. [28]*

*A team of physicists from ICTP-Trieste and IQOQI-Innsbruck has come up with a surprisingly simple idea to investigate quantum entanglement of many particles. [27]*

*For the first time, physicists have experimentally demonstrated ternary—rather than binary—quantum correlations between entangled objects. [26]*

*The physicists, Sally Shrapnel, Fabio Costa, and Gerard Milburn, at The University of Queensland in Australia, have published a paper on the new quantum probability rule in the New Journal of Physics. [25]*

*Researchers have studied how a 'drumstick' made of light could make a microscopic 'drum' vibrate and stand still at the same time. [24]*

*A University of Oklahoma physicist, Alberto M. Marino, is developing quantum-enhanced sensors that could find their way into applications ranging from biomedical to chemical detection. [23]*

*A team of researchers from Shanghai Jiao Tong University and the University of Science and Technology of China has developed a chip that allows for two-dimensional quantum walks of single photons on a physical device. [22]*

*The physicists, Sally Shrapnel, Fabio Costa, and Gerard Milburn, at The University of Queensland in Australia, have published a paper on the new quantum probability rule in the New Journal of Physics. [21]*

*Probabilistic computing will allow future systems to comprehend and compute with uncertainties inherent in natural data, which will enable us to build computers capable of understanding, predicting and decision-making. [20]*

*For years, the people developing artificial intelligence drew inspiration from what was known about the human brain, and it has enjoyed a lot of success as a result. Now, AI is starting to return the favor. [19]*

*Scientists at the National Center for Supercomputing Applications (NCSA), located at the University of Illinois at Urbana-Champaign, have pioneered the use of GPU-accelerated deep learning for rapid detection and characterization of gravitational waves. [18]*

*Researchers from Queen Mary University of London have developed a mathematical model for the emergence of innovations. [17]*

*Quantum computers can be made to utilize effects such as quantum coherence and entanglement to accelerate machine learning. [16]*

*Neural networks learn how to carry out certain tasks by analyzing large amounts of data displayed to them. [15]*

*Who is the better experimentalist, a human or a robot? When it comes to exploring synthetic and crystallization conditions for inorganic gigantic molecules, actively learning machines are clearly ahead, as demonstrated by British Scientists in an experiment with polyoxometalates published in the journal *Angewandte Chemie*. [14]*

*Machine learning algorithms are designed to improve as they encounter more data, making them a versatile technology for understanding large sets of photos such as those accessible from Google Images. Elizabeth Holm, professor of materials science and engineering at Carnegie Mellon University, is leveraging this technology to better understand the enormous number of research images accumulated in the field of materials science. [13]*

*With the help of artificial intelligence, chemists from the University of Basel in Switzerland have computed the characteristics of about two million crystals made up of four chemical elements. The researchers were able to identify 90 previously unknown thermodynamically stable crystals that can be regarded as new materials. [12]*

*The artificial intelligence system's ability to set itself up quickly every morning and compensate for any overnight fluctuations would make this fragile technology much more useful for field measurements, said co-lead researcher Dr Michael Hush from UNSW ADFA. [11]*

*Quantum physicist Mario Krenn and his colleagues in the group of Anton Zeilinger from the Faculty of Physics at the University of Vienna and the Austrian Academy of Sciences have developed an algorithm which designs new useful quantum experiments. As the computer does not rely on human intuition, it finds novel unfamiliar solutions. [10]*

*Researchers at the University of Chicago's Institute for Molecular Engineering and the University of Konstanz have demonstrated the ability to generate a quantum logic operation, or rotation of the qubit, that - surprisingly—is intrinsically resilient to noise as well as to variations in the strength or duration of the control. Their achievement is*

*based on a geometric concept known as the Berry phase and is implemented through entirely optical means within a single electronic spin in diamond. [9]*

*New research demonstrates that particles at the quantum level can in fact be seen as behaving something like billiard balls rolling along a table, and not merely as the probabilistic smears that the standard interpretation of quantum mechanics suggests. But there's a catch - the tracks the particles follow do not always behave as one would expect from "realistic" trajectories, but often in a fashion that has been termed "surrealistic." [8]*

*Quantum entanglement—which occurs when two or more particles are correlated in such a way that they can influence each other even across large distances—is not an all-or-nothing phenomenon, but occurs in various degrees. The more a quantum state is entangled with its partner, the better the states will perform in quantum information applications. Unfortunately, quantifying entanglement is a difficult process involving complex optimization problems that give even physicists headaches. [7]*

*A trio of physicists in Europe has come up with an idea that they believe would allow a person to actually witness entanglement. Valentina Caprara Vivoli, with the University of Geneva, Pavel Sekatski, with the University of Innsbruck and Nicolas Sangouard, with the University of Basel, have together written a paper describing a scenario where a human subject would be able to witness an instance of entanglement—they have uploaded it to the arXiv server for review by others. [6]*

*The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the Wave-Particle Duality and the electron's spin also, building the Bridge between the Classical and Quantum Theories.*

*The Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass rate and the Weak and Strong Interactions by the diffraction patterns. The Weak Interaction changes the diffraction patterns by moving the electric charge from one side to the other side of the diffraction pattern, which violates the CP and Time reversal symmetry.*

*The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the relativistic quantum theory.*

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## Preface

Physicists are continually looking for ways to unify the theory of relativity, which describes largescale phenomena, with quantum theory, which describes small-scale phenomena. In a new proposed experiment in this area, two toaster-sized "nanosatellites" carrying entangled condensates orbit around the Earth, until one of them moves to a different orbit with different gravitational field strength. As a result of the change in gravity, the entanglement between the condensates is predicted to degrade by up to 20%. Experimentally testing the proposal may be possible in the near future. [5]

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

I think that we have a simple bridge between the classical and quantum mechanics by understanding the Heisenberg Uncertainty Relations. It makes clear that the particles are not point like but have a  $dx$  and  $dp$  uncertainty.

## Quantum science turns social

Researchers in a lab at Aarhus University have developed a versatile remote gaming interface that allowed external experts as well as hundreds of citizen scientists all over the world to optimize a quantum gas experiment through multiplayer collaboration and in real time. The efforts of both teams dramatically improved upon the previous best solutions established after months of careful experimental optimization. Comparing domain experts, algorithms and citizen scientists is a first step towards unraveling how humans solve complex, natural science problems.

In a future characterized by algorithms with ever-increasing computational power, it is essential to understand the difference between human and machine intelligence. This will enable the development of hybrid intelligence interfaces that optimally exploit the best of both worlds. By making complex research challenges available for contribution by the general public, [citizen science](#) does exactly this. Numerous citizen science projects have shown that humans can compete with state-of-the-art algorithms to solve complex, natural science problems.

However, these projects have so far not addressed why a collective of citizen scientists can solve such complex problems. An interdisciplinary team of researchers from Aarhus University, Ulm

University, and the University of Sussex, Brighton have now taken important first steps in this direction by analyzing the performance and search strategy of both a state-of-the-art computer algorithm and citizen scientists in their real-time optimization of an experimental laboratory setting.

### **The Alice Challenge**

In the Alice Challenge, Robert Heck and colleagues gave experts and citizen scientists live access to their ultra-cold quantum gas experiment. This was made possible via a novel remote interface created by the team at ScienceAtHome of Aarhus University. By manipulating laser beams and magnetic fields, the task was to cool as many atoms as possible down to extremely cold temperatures just above absolute zero at  $-273.15^{\circ}\text{C}$ . This so-called Bose-Einstein condensate (BEC) is a distinct state of matter (like solid, liquid, gas or plasma) that constitutes an ideal candidate for performing such things as quantum simulation experiments and high-precision measurements.

As detailed below both groups successfully used the remote interface to improve on previously optimal solutions. In this first-ever citizen science experimental optimization challenge with real-time feedback, the researchers further quantified the behavior of citizen scientists. They concluded that what makes human problem solving unique is that a collective of individuals can balance innovative attempts and refine existing solutions based on their previous performance.

### **Quantum optimization as a remote service**

Quantum technology is increasingly stepping out of university labs and into the corporate world. For high-performance and robust applications, exceptional levels of control of the complex systems are needed, as well as new methodologies in both theoretical and experimental science. This requires interdisciplinary and often trans-institutional collaborations, which in turn necessitates the development of efficient interfaces to allow each of the experts to contribute as efficiently as possible.

In recent years, remote interfaces for experimental apparatuses have started to appear. However, they are always focused either on educational settings or the investigation of a very particular experimental setup.

In contrast, Robert Heck and colleagues in the current work set out to develop a flexible remote interface and a powerful optimization algorithm that can potentially be applied to many other settings in the future. The experimental production of BECs serves as an ideal test-bench:



Game interface of the Alice Challenge. Players could manipulate three curves representing two laser beam intensities and the strength of a magnetic field gradient, respectively. The chosen curves were then realized in the laboratory in real-time. Credit: Robert Heck, AUThe **RedCRAB package**

"Making machines play the Alice Challenge alongside humans over the internet required us to create a new software package, RedCRAB, for remote optimization of quantum experiments," explained Tommaso Calarco and Simone Montangero, leaders of the Ulm optimization team.

RedCRAB is ideally suited for problems with many control parameters when the exact theoretical modelling of the system is unknown and other traditional optimization methods fail. It furthermore has the advantage that the optimization experts can easily adjust algorithmic parameters and exploit its full potential without requiring intermediate communication with the experimental team. Moreover, the efficiency of the optimization can be analyzed, and based on that, algorithmic improvements can be made and easily transferred to future experiments.

Tommaso Calarco is extremely excited about the results:

"RedCRAB optimization worked so well that it is now applied in several labs around the world to enhance the performance of quantum devices. We plan to extend this as a cloud service that we believe will likely result in faster development of the theoretical understanding, of the algorithmic development and overall of quantum science and technologies."

### Can any research challenge be turned into a game?

As mentioned above, game interfaces have in recent years have enabled non-experts to use their creativity and intuition to contribute to various scientific fields. In 2016, the Aarhus research group reported the results of the first quantum citizen science game, Quantum Moves, in *Nature*. In the game, the players contributed to finding fast and efficient solutions to atomic transport in a quantum computing architecture.

The clear water-like analogy of that particular game and the scarcity of other quantum games has since sparked the criticism that perhaps non-experts can only contribute in research topics for which a clear classical analogy can be established. Since this can rarely be established for any given



research challenge, it could seem that the gamification approach is of very limited general applicability and Quantum Moves was just a very special case.

To test this hypothesis, the remote interface to the ultra-cold atoms experiment in Aarhus was turned into a citizen science game, the Alice Challenge. Concretely, the players controlled laser intensities and magnetic fields of the experimental sequence. As illustrated in the figure the "game" interface is far from intuitive and perhaps not very entertaining. The players drag one or more of the curves, push the submit button. Then the solution was sent to the lab, the experiment conducted, and roughly 35 seconds later the result is communicated to the player.

### **Two weeks of gaming – and better solutions**

Robert Heck, one of the lead scientists in designing the Alice Challenge and first author of the paper:

"This realizes the first ever citizen science experimental optimization challenge with real-time feedback in any field. In the Alice Challenge 600 citizen scientists had over two weeks access to our lab in Aarhus. Within this time, 7577 solutions were submitted and realized in the lab. It was also a challenge for us. As our participants came from all over the world we had to keep the experiment online for two weeks straight without interruptions."

Although the players did not have any formal training in experimental physics they still consistently managed to find surprisingly good solutions. Why? One hint came from an interview with a top-player, a retired Italian microwave system engineer. He said, that for him participating in the Alice Challenge reminded him a lot of his previous job as an engineer. He never attained a detailed understanding of microwave systems but instead spent years developing an intuition of how to optimize the performance of his "black-box".

"This is extremely exciting. We humans may develop general optimization skills in our everyday work life that we can efficiently transfer to new settings. If this is true, any research challenge can in fact be turned into a citizen science game," said Jacob Sherson, head of the ScienceAtHome project.

### **Are citizen scientists really better?**

How can untrained amateurs using an unintuitive game interface outcompete expert experimentalists? One answer may lie in an old Herbert Simon quote: "Solving a problem simply means representing it so as to make the solution transparent". In this view, the players may be performing better, not because they have superior skills but because the interface they are using makes another kind of exploration "the obvious thing to try out" compared to the traditional experimental control interface.

"The process of developing fun interfaces that allow experts and citizen scientists alike to view the complex research problems from different angles, may contain the key to developing future hybrid intelligence systems in which we make optimal use of human creativity," explained Jacob Sherson.

### **Social science in the wild**

Another reason for the success of the citizen scientists is likely due to the multiplayer collaboration that the remote interface facilitated. Testing this hypothesis involved a substantial advancement compared to traditional social science.

Carsten Bergenholtz and Oana Vuculescu, the social science experts of the project:

"In the social sciences we are interested in how people solve problems. However, we often invite them into a social science lab to solve artificial problems, which are not directly connected to the real world. Furthermore, individuals in the lab usually solve these artificial problems alone. In contrast, our Alice Challenge was a unique opportunity to do social sciences 'in the wild', i.e. players solved a real problem and we allowed players to collaborate and learn from each other. Overall, this enables us to address why a collective of citizen scientists are surprisingly good at solving such complex problems."

The researchers find that individuals at the top or bottom of the leaderboard behave differently. Well-performing players engage in small changes to their proposed solutions whereas poorly-performing players explore the unknown and apply larger changes. As poorly performing players move upwards in the ranks and, vice versa, well-performing players move downwards individuals adapt their search accordingly.

On a collective level, this means there are always some players at the top of a leaderboard that optimize the current best solution as well as some players at the bottom of a leaderboard that innovate and try out completely new solutions. This was directly compared to the behavior of the RedCRAB algorithm that was much more local in nature - focusing on small steps to iteratively improve the current solution instead of broadly searching the overall landscape.

### **A unique insight**

"These findings provide insight into the unique human ability to collectively solve complex problems. Leveraging this knowledge will allow for the design of hybrid intelligence interfaces that combine the computational strengths of AI with the advantages of human intuition," said Carsten Bergenholtz and Oana Vuculescu.

Mark Bason at University of Sussex is looking into the future:

"Progress in science is very frequently the result of close collaboration between established groups, such as those from academia or industry. However, technology has advanced so far that many new interactions are possible. By opening up our research, we can now benefit from the skills of players, algorithms and hybrid approaches of the two." [29]

### **Spooky quantum particle pairs fly like weird curveballs**

Curvy baseball pitches have surprising things in common with quantum particles described in a new physics study, though the latter fly much more weirdly.

In fact, ultracold paired particles called fermions must behave even weirder than physicists previously thought, according to theoretical physicists from the Georgia Institute of Technology, who mathematically studied their flight patterns. Already, flying quantum particles were renowned for their weirdness.

To understand why, start with similarities to a baseball then add significant differences.

A pitcher imparts spin, momentum, and energy to a baseball when throwing a curveball, a change-up, or a slider. Fermions' funny flights are likewise carved by spins, momenta, and energies, but also by powerful quantum eccentricities like entanglement, which Albert Einstein once called "spooky action at a distance" between quantum particles.

In the new study, the researchers even predicted that the particles can act like different quantum balls called bosons to mimic the manner that photons, or particles of light, fly. A simplified explanation of these ultracold paired particles and their odd flights is below.

### Light-matter modeling

Those influences all combine to give fermions a trajectory repertoire much odder than that of any master baseball pitcher, and the new study maps it out and opens new ways to observe it experimentally. The Georgia Tech team took the offbeat approach of adding quantum optical—or light-like – ideas to their predictive calculations of these specks of matter and arrived at eyebrow-raising, insightful results.

"The particle behavior we predicted is just schizophrenic," said Uzi Landman, Regents' and Institute Professor and F.E. Callaway Endowed Chair in Georgia Tech's School of Physics.

Mathematical and theoretical details can be found in the study in the journal *Physical Review A*, which Landman, first author Benedikt Brandt, who is a graduate research assistant, and senior scientist Constantine Yannouleas published on May 4, 2018. Their research was funded by the Air Force Office of Scientific Research.

### Flying fermions explained

Tracing quantum curveballs is counterintuitive by nature with concepts like fermions, bosons, spins, spooky entanglement, and particle-wave duality. So, let's go step-by-step to understand them and the study's insights.

The ballgame revolves around fermion pairs. Fermions can be subatomic particles or whole atoms. In this case, the physicists modeled using atoms.

The term fermion refers to quantum-statistical properties that the particle has as opposed the properties of its counterpart particle called a boson, in particular the particle's spin, which is called half-integer for fermions and full-integer for bosons. (These spins aren't exactly like those on a ball. For more, see: Fermions and Bosons for Dummies.)

"Photons and Higgs bosons are examples of bosons," Landman said. "Bosons are gregarious: Two or more bosons can share the exact same space. This allows many of them to be superimposed onto each other on the same tiny spot."

"Fermions, on the other hand, are standoffish. They lay claim to their own space, and don't share it with other particles. Fermions can be stacked upon each other but do not occupy the same space."

Electrons, protons, neutrons, and some atoms are common examples of fermions.

### Laser-tweezing baseballs

The theoretical study envisions two fermionic atoms starting out carefully held next to each other by two pairs of "tweezers" made of intersecting laser beams, as is actually done in applicable

physics experiments. In the study's theoretical setup, lasers and special magnetic fields would also be used to slow the fermions to a near halt, making them "ultracold" at 0.000000001 degrees Kelvin, or -273.15 degrees Celsius (-459.67 degrees Fahrenheit).

That's a sliver above absolute zero, the lowest possible temperature in the universe, and particles that cold do strange things.

"A particle's motion is usually frantic, but the cooling slows it down almost to a stand-still," said Landman, who is also director of the Georgia Tech Center for Computational Materials Science. "And these particles also have wave properties, and at that temperature, the wavelength grows enormously long."

"The waves become microns in size. That would be like a pebble growing to be a third of the size of this country. When that happens, the atom actually becomes visible under an optical microscope."

The inflated size makes it easier for researchers to know the two particles' starting locations. When they turn the laser tweezers off, the fermions fly away. The particles' wave properties also have a lot to do with their weird flights.

"A particle in motion will act as a projectile under certain circumstances. But in others, it will behave like a wave," Landman said. "We call it the quantum world duality."

### **Together or apart**

"If you set up two detectors at different positions but the same distance from the particle pair, how often the two fly into the same detector or how often they fly into separate ones says a lot about those particles," Landman said. "And that's where our weird findings come in."

Fermions are expected to fly differently from bosons, but the theoretical physicists' study on fermions revises this idea. Depending on the degree of quantum entanglement between the two fermions before they're released and depending on their energy level, they can act like fermions or act like bosons.

"This adds new weirdness to the already established schizophrenic particle-wave duality," Landman said.

"A pair of photons (which are bosons) fly to the same place. They stay as a pair," Landman said.

"They're social animals, and you find them either both in the one detector or both in the other. We call this phenomenon 'bunching.'"

### **Weirdo flight paths**

Fermions are often expected to do the opposite, referred to as anti-bunching, but according to the study, how they fly depends on whether or not they have spooky interaction and, if so, whether the interaction is attractive or repulsive.

"If they're interacting, and depending on the starting energy level, we predict that they may do strange things when they fly," Landman said. "That's new."

"At the base energy level, called ground state, our two fermions that interact with ultra-strong repulsion behave fermionically, meaning they avoid each other. Now, if they interact with strong attraction, they aggregate the way bosons do," Landman said. "So far, all as expected."

But bumping up the trapped particles' level of energy, or excitation, via an additional laser or a magnetic field, would appear to heighten the particles' weirdness. The excitation levels can twist the rules of what interactions do to a fermion's flight, according to the theoretical study.

For example, the above mentioned fermionic behavior usually connected with strong repulsive interaction could turn bosonic, according to the physicists' calculations. In other words, the two particles would fly to the same detector the way bosons do.

### Orderly quantum schizophrenia

"As crazy as all this looks, there appears to be strong reliability in these behaviors that could even be predictably and practically manipulated," Landman said.

As with a pitcher who finesses a screwball's path, physicists could determine a fermion's weird flight using quantum mechanical formulation, advanced computational simulation, and experimentation, the study said.

"It looks like you may even be able to engineer what this quantum weirdness does," Landman said.

"If you know particle states reliably, you may be able to use them as a resource for quantum computations and information storage and retrieval." [28]

### Turning entanglement upside down

A team of physicists from ICTP-Trieste and IQOQI-Innsbruck has come up with a surprisingly simple idea to investigate quantum entanglement of many particles. Instead of digging deep into the properties of quantum wave functions, which are notoriously hard to experimentally access, they propose to realize physical systems governed by the corresponding entanglement Hamiltonians. By doing so, entanglement properties of the original problem of interest become accessible via well-established tools.

Quantum entanglement forms the heart of the second quantum revolution: it is a key characteristic used to understand forms of quantum matter, and a key resource for present and future quantum technologies. Physically, entangled particles cannot be described as individual particles with defined states, but only as a single system. Even when the particles are separated by a large distance, changes in one particle also instantaneously affect the other particle(s). The entanglement of individual particles—whether photons, atoms or molecules—is part of everyday life in the laboratory today. In many-body physics, following the pioneering work of Li and Haldane, entanglement is typically characterized by the so-called entanglement spectrum: it is able to capture essential features of collective quantum phenomena, such as topological order, and at the same time, it allows to quantify the 'quantumness' of a given state—that is, how challenging it is to simply write it down on a classical computer.

Despite its importance, the experimental methods to measure the entanglement spectrum quickly reach their limits—until today, these spectra have been measured only in few qubits systems. With an increasing number of particles, this effort becomes hopeless as the complexity of current techniques increases exponentially.

"Today, it is very hard to perform an experiment beyond few particles that allows us to make concrete statements about entanglement spectra," explains Marcello Dalmonte from the International Centre for Theoretical Physics (ICTP) in Trieste, Italy. Together with Peter Zoller and Benoît Vermersch at the University of Innsbruck, he has now found a surprisingly simple way to investigate [quantum entanglement](#) directly. The physicists turn the concept of quantum simulation upside down by no longer simulating a certain physical system in the quantum simulator, but directly simulating its entanglement Hamiltonian operator, whose spectrum of excitations immediately relates to the entanglement spectrum.

"Instead of simulating a specific quantum problem in the laboratory and then trying to measure the entanglement properties, we propose simply turning the tables and directly realizing the corresponding entanglement Hamiltonian, which gives immediate and simple access to entanglement properties, such as the entanglement spectrum," explains Marcello Dalmonte. "Probing this operator in the lab is conceptually and practically as easy as probing conventional many-body spectra, a well-established lab routine."

Furthermore, there are hardly any limits to this method with regard to the size of the quantum system. This could also allow the investigation of [entanglement](#) spectra in many-particle systems, which is notoriously challenging to address with classical computers. Dalmonte, Vermersch and Zoller describe the radically new method in a current paper in *Nature Physics* and demonstrate its concrete realization on a number of experimental platforms, such as atomic systems, trapped ions and also solid-state systems based on superconducting quantum bits. [27]

## **Stronger-than-binary correlations experimentally demonstrated for the first time**

For the first time, physicists have experimentally demonstrated ternary—rather than binary—quantum correlations between entangled objects. The results show that the quantum measurement process cannot be described as a binary process (having two possible outcomes), but rather stronger-than-binary ternary measurements (which have three possible outcomes) should be considered in order to fully understand how the quantum measurement process works.

The physicists, Xiao-Min Hu and coauthors from China, Germany, Spain, and Hungary, have published a paper on the stronger-than-binary correlations in a recent issue of *Physical Review Letters*.

"We discovered and experimentally verified the existence of genuine ternary measurements," coauthor Matthias Kleinmann at the University of Siegen in Siegen, Germany, and the University of the Basque Country in Bilbao, Spain, told *Phys.org*. "The experimental conclusions are independent

of any underlying theory (here: [quantum theory](#)) and establish that ternary measurements are a generic feature of nature."

Before now, stronger-than-binary correlations have been theoretically predicted to exist, but this is the first time that they have been experimentally observed. In their experiments, the researchers entangled two photonic qutrits, each of which has three possible states (0, 1, and 2), instead of just two (0 and 1) as for qubits. They then sent the qutrits to different laboratories where they measured the state of each qutrit, enabling them to determine the strength of the correlations between the two qutrits.

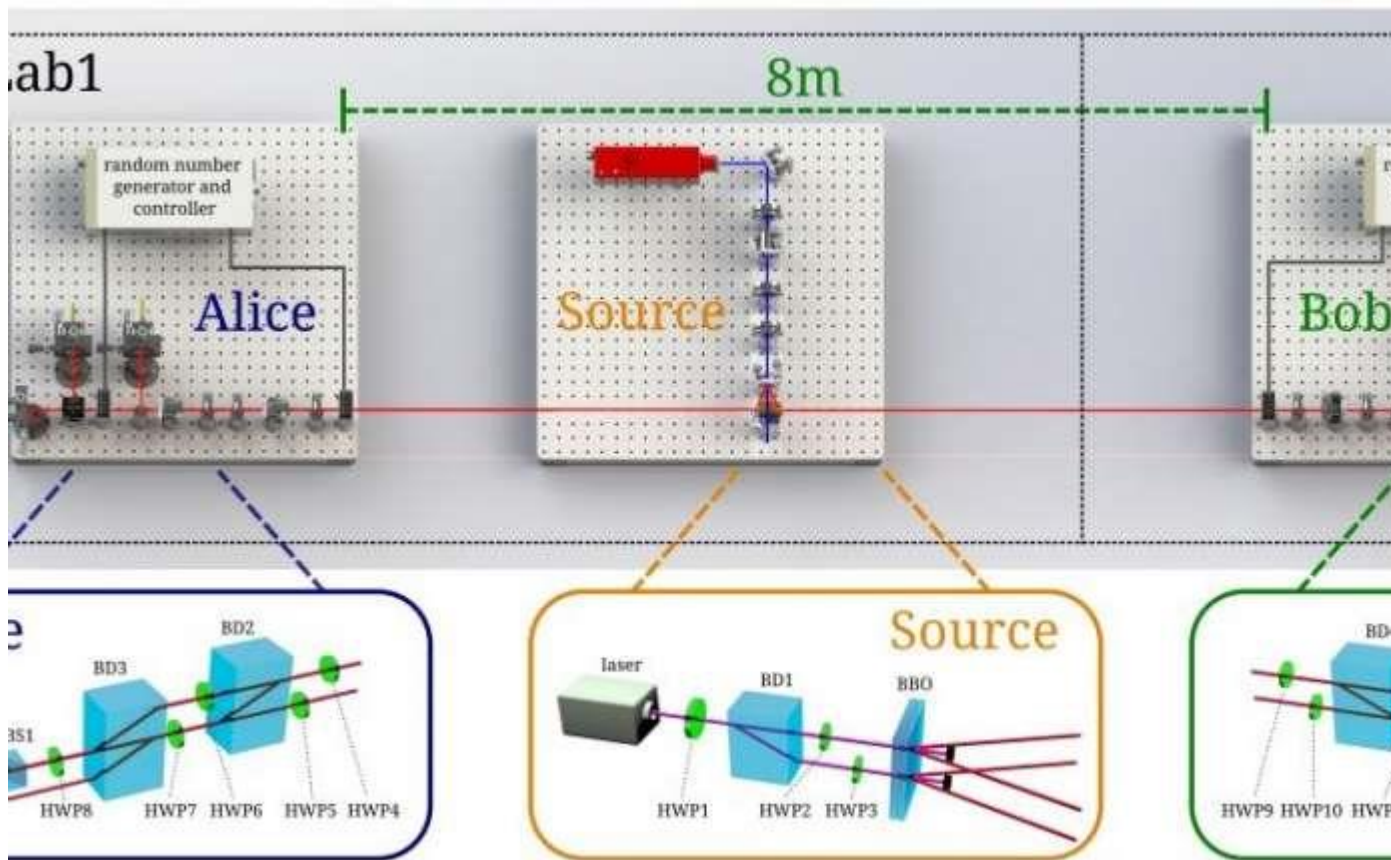


Illustration of the experimental setup for demonstrating ternary correlations. Credit: Hu et al. ©2018 American Physical Society

If the [quantum](#) measurement process were binary, then measurements could be described as a two-step process in which first one of the three possible measurement outcomes is ruled out by a classical mechanism, and then a quantum binary measurement selects between the two remaining outcomes. In this binary measurement process, the maximum [correlation](#) between two entangled objects cannot exceed a certain value.

In their experiments, the researchers demonstrated that the strength of the correlations between the entangled qutrits exceed this maximum value. To do this, they performed a Bell-type

experiment in which they showed that the observed correlations violate the maximum inequality for nonsignalling binary correlations with a very high statistical significance, corresponding to 9.3 standard deviations. The results imply that the measurement process in quantum theory cannot be explained by the two-step process with binary measurements. Instead, the measurement process here is genuinely ternary, where the quantum ternary measurement selects between all three of the possible states at once.

Overall, the researchers explain that the observations of stronger-than-binary correlations don't contradict previous experimental evidence of binary correlations, but add new possibilities for how the quantum measurement process works at the most fundamental level.

"Now that we have established the theoretical tools and the experimental methods to understand and create ternary correlations, we aim to proceed in two directions," Kleinmann said. "First, we hope for technological applications (for example, in randomness extraction) and second, we are now using our results as a new basis for a deeper understanding of quantum theory." [26]

## **New quantum probability rule offers novel perspective of wave function collapse**

Quantum theory is based heavily on probabilities, since measuring a quantum system doesn't produce the same outcome every time, but instead yields one of many outcomes that each occur with a certain probability. Now in a new paper, physicists have presented a new quantum probability rule for assigning probabilities to measurement outcomes, or events, that essentially combines two of the most important quantum probability rules (the Born rule and the wave function collapse rule) into one.

The physicists, Sally Shrapnel, Fabio Costa, and Gerard Milburn, at The University of Queensland in Australia, have published a paper on the new [quantum probability](#) rule in the *New Journal of Physics*.

One of the most important probability rules in quantum [theory](#) is the Born rule, which gives the probability that a measurement yields a certain event. However, things get a little bit more complicated when predicting consecutive events. Although in classical scenarios it's possible to assign joint probabilities to consecutive events using conditioning, in quantum scenarios this is not possible since each measurement necessarily disturbs the system. So in quantum mechanics, the state must be updated with this new information after every measurement.

In order to update the state, a "state update rule" or "[collapse](#) rule" is applied. In the new paper, the physicists explain that this update is basically an "ad hoc ingredient," since it is introduced as an axiom (which cannot be proved), and is a completely separate entity from the Born rule. Although this additional rule works well for practical purposes, it poses problems for understanding the true nature of quantum theory—in particular, for interpretations of quantum theory as a statement about the knowledge of reality, rather than of reality itself.



To address these problems, the physicists propose and prove a unified probability rule, which they call the "Quantum Process Rule." They show that this rule is more fundamental than the Born rule, as both the Born rule and the state update, or collapse, rule can be derived from this new rule—that is, the update rule does not need to be independently introduced. Unlike the Born rule, the Quantum Process Rule can assign joint probabilities to consecutive events.

One of the interesting implications of showing that wave function collapse follows from the new probability rule is that it suggests that the collapse does not need to be regarded as a fundamental aspect of quantum theory. This implication offers an alternative perspective of wave function collapse, as well as a new understanding of the nature of [quantum theory](#).

"The main significance of the work is that we derive a single, unified probability rule that subsumes both the Born rule and the collapse rule," Shrapnel told Phys.org. "This means that one no longer needs to explain wave function collapse in terms of a physical process, but can instead view this part of the formalism as simply a case of classical probabilistic conditioning. It is this latter possibility that means we can consider the quantum state as being about our knowledge rather than a direct description of physical reality." [25]

## Can a quantum drum vibrate and stand still at the same time?

Researchers have studied how a 'drumstick' made of light could make a microscopic 'drum' vibrate and stand still at the same time.

A team of researchers from the UK and Australia have made a key step towards understanding the boundary between the [quantum](#) world and our everyday classical world.

Quantum mechanics is truly weird. Objects can behave like both particles and waves, and can be both here and there at the same time, defying our common sense. Such counterintuitive behaviour is typically confined to the microscopic realm and the question "why don't we see such behaviour in everyday objects?" challenges many scientists today.

Now, a team of researchers have developed a new technique to generate this type of quantum behaviour in the motion of a tiny drum just visible to the naked eye. The details of their research are published today in *New Journal of Physics*.

Project principal investigator, Dr. Michael Vanner from the Quantum Measurement Lab at Imperial College London, said: "Such systems offer significant potential for the development of powerful new quantum-enhanced technologies, such as ultra-precise sensors, and new types of transducers.

"Excitingly, this research direction will also enable us to test the fundamental limits of quantum mechanics by observing how quantum superpositions behave at a large scale."

Mechanical vibrations, such as those that create the sound from a drum, are an important part of our everyday experience. Hitting a drum with a drumstick causes it to rapidly move up and down, producing the sound we hear.

In the quantum world, a drum can vibrate and stand still at the same time. However, generating such quantum motion is very challenging. lead author of the project Dr. Martin Ringbauer from the

University of Queensland node of the Australian Research Council Centre for Engineered Quantum Systems, said: "You need a special kind of drumstick to make such a quantum vibration with our tiny drum."

In recent years, the emerging field of quantum optomechanics has made great progress towards the goal of a quantum drum using laser light as a type of drumstick. However, many challenges remain, so the authors' present study takes an unconventional approach.

Dr. Ringbauer continues: "We adapted a trick from [optical quantum computing](#) to help us play the quantum drum. We used a measurement with single particles of light—photons—to tailor the properties of the drumstick.

"This provides a promising route to making a mechanical version of Schrodinger's cat, where the drum vibrates and stands still at the same time."

These experiments have made the first observation of mechanical interferences fringes, which is a crucial step forward for the field.

In the experiment, the fringes were at a classical level due to thermal noise, but motivated by this success, the team are now working hard to improve their technique and operate the experiments at temperatures close to absolute zero where quantum mechanics is expected to dominate.

These future experiments may reveal new intricacies of [quantum mechanics](#) and may even help light the path to a theory that links the [quantum world](#) and the physics of gravity. [24]

## Physicists developing quantum-enhanced sensors for real-life applications

A University of Oklahoma physicist, Alberto M. Marino, is developing quantum-enhanced sensors that could find their way into applications ranging from biomedical to chemical detection.

In a new study, Marino's team, in collaboration with the U.S. Department of Energy's Oak Ridge National Laboratory, demonstrates the ability of quantum states of light to enhance the sensitivities of state-of-the-art plasmonic sensors. The team presents the first implementation of a sensor with sensitivities considered state-of-the-art and shows how quantum-enhanced sensing can find its way into real-life applications.

"Quantum resources can enhance the sensitivity of a device beyond the classical shot noise limit and, as a result, revolutionize the field of metrology through the development of quantum enhanced sensors," said Marino, a professor in the Homer L. Dodge Department of Physics and Astronomy, OU College of Arts and Sciences. "In particular, [plasmonic](#) sensors offer a unique opportunity to enhance real-life devices."

Plasmonic sensors are currently used in a number of applications, such as biosensing, atmospheric monitoring, ultrasound diagnostics and chemical detection. These [sensors](#) can be probed with light and have been shown to operate at the shot noise limit. Thus, when interfaced with quantum states of light that exhibit reduced noise properties, the noise floor can be reduced below the classical shot [noise](#) limit. This makes it possible to obtain a quantum-based enhancement of the [sensitivity](#).

A study on this project, "Quantum-Enhanced Plasmonic Sensing," has been published in the scientific journal *Optica*. [23]

## **A chip that allows for two-dimensional quantum walks**

A team of researchers from Shanghai Jiao Tong University and the University of Science and Technology of China has developed a chip that allows for two-dimensional quantum walks of single photons on a physical device. In their paper published on the open access site, *Science Advances* the group describes the chip and why they believe developing it was important.

Quantum walks are the quantum version of classical random walks, which are a mathematical means for describing a natural random walk, e.g., simply wandering around randomly. To describe such walks, mathematicians and computer scientists use probability distribution grids that show a current position and possible next steps. Quantum walks are used to build models that depict randomly grown, sophisticated and complex networks such as the human neural [network](#). They can also be used to create networks for actual use in applications, and might one day be used in quantum-based robots.

As the researchers note, a quantum computer should provide exponential advantages over classical systems due to their nature. To that end, scientists have been working to implement quantum walks in a physical machine as part of developing a truly useful quantum computer. In this new effort, the researchers report that they have developed a [chip](#) that carries out quantum walks on a two-dimensional 49x49 grid—the largest created so far by any team.

The three-dimensional chip, the team reports, was created using a technique called femtosecond writing. It uses the external geometry of photonic waveguide arrays as a means for carrying out the quantum walks using a single photon. They note also that they tested the chip by observing patterns and variance profiles and comparing them to simulation studies. They suggest further that in addition to making progress toward a truly useful quantum [computer](#), the chip could also be used to boost the performance of analog quantum computing or quantum simulators.

If researchers can create [quantum](#) computers with very large, or even unlimited size grids, it might be possible to create and use networks as complex as the human nervous system. [22]

## New quantum probability rule offers novel perspective of wave function collapse

Quantum theory is based heavily on probabilities, since measuring a quantum system doesn't produce the same outcome every time, but instead yields one of many outcomes that each occur with a certain probability. Now in a new paper, physicists have presented a new quantum probability rule for assigning probabilities to measurement outcomes, or events, that essentially combines two of the most important quantum probability rules (the Born rule and the wave function collapse rule) into one.

The physicists, Sally Shrapnel, Fabio Costa, and Gerard Milburn, at The University of Queensland in Australia, have published a paper on the new [quantum probability](#) rule in the *New Journal of Physics*.

One of the most important probability rules in quantum [theory](#) is the Born rule, which gives the probability that a measurement yields a certain event. However, things get a little bit more complicated when predicting consecutive events. Although in classical scenarios it's possible to assign joint probabilities to consecutive events using conditioning, in quantum scenarios this is not possible since each measurement necessarily disturbs the system. So in quantum mechanics, the state must be updated with this new information after every measurement.

In order to update the state, a "state update rule" or "[collapse](#) rule" is applied. In the new paper, the physicists explain that this update is basically an "ad hoc ingredient," since it is introduced as an axiom (which cannot be proved), and is a completely separate entity from the Born rule. Although this additional rule works well for practical purposes, it poses problems for understanding the true nature of quantum theory—in particular, for interpretations of quantum theory as a statement about the knowledge of reality, rather than of reality itself.

To address these problems, the physicists propose and prove a unified probability rule, which they call the "Quantum Process Rule." They show that this rule is more fundamental than the Born rule, as both the Born rule and the state update, or collapse, rule can be derived from this new rule—that is, the update rule does not need to be independently introduced. Unlike the Born rule, the Quantum Process Rule can assign joint probabilities to consecutive events.

One of the interesting implications of showing that wave function collapse follows from the new probability rule is that it suggests that the collapse does not need to be regarded as a fundamental aspect of quantum theory. This implication offers an alternative perspective of wave function collapse, as well as a new understanding of the nature of [quantum theory](#).

"The main significance of the work is that we derive a single, unified probability rule that subsumes both the Born rule and the collapse rule," Shrapnel told Phys.org. "This means that one no longer needs to explain wave function collapse in terms of a physical process, but can instead view this part of the formalism as simply a case of classical probabilistic conditioning. It is this latter possibility that means we can consider the quantum state as being about our knowledge rather than a direct description of physical reality." [21]

## Probabilistic computing takes artificial intelligence to the next step

The potential impact of Artificial Intelligence (AI) has never been greater—but we'll only be successful if AI can deliver smarter and more intuitive answers.

A key barrier to AI today is that natural data fed to a computer is largely unstructured and "noisy."

It's easy for humans to sort through natural data. For example: If you are driving a car on a residential street and see a ball roll in front of you, you would stop, assuming there is a small child not far behind that ball. Computers today don't do this. They are built to assist humans with precise productivity tasks. Making computers efficient at dealing with probabilities at scale is central to our ability to transform current systems and applications from advanced computational aids into intelligent partners for understanding and decision-making.

This is why probabilistic computing is one key component to AI and central to addressing these challenges. Probabilistic computing will allow future systems to comprehend and compute with uncertainties inherent in natural data, which will enable us to build computers capable of understanding, predicting and decision-making.

Today at Intel, we are observing an unprecedented growth of applications that rely on analysis of noisy natural data – different and even conflicting information. Such applications aim to assist humans with a higher level of intelligence and awareness about the environments in which they operate. Cutting through this noisy minefield is central to our ability to transform computers into intelligent partners that can understand and act on information with human-like fidelity.

Research into probabilistic computing is not a new area of study, but the improvements in high-performance computing and [deep learning algorithms](#) may lead probabilistic computing into a new era. In the next few years, we expect that research in probabilistic computing will lead to significant improvements in the reliability, security, serviceability and performance of AI systems, including hardware designed specifically for probabilistic computing. These advancements are critical to deploying applications into the real world – from smart homes to smart cities.

To accelerate our work in probabilistic computing, Intel is increasing its research investment in probabilistic computing and we are working with partners to pursue this goal.

### Establishing the Intel Strategic Research Alliance for Probabilistic Computing

Realizing the full potential of probabilistic computing involves holistic integration of multiple levels in computing technology. Today, Intel underscored its commitment to integrated and collaborative implementation of emerging computing architectures and a sound ecosystem enablement strategy by issuing a call to the academic and start-up communities to partner with us to advance probabilistic computing from the lab to reality across these vectors: benchmark applications, adversarial attack mitigations, probabilistic frameworks and software and hardware optimization.

### An Eye on What's Next

We are incredibly eager to see the proposals to advance probabilistic computing and to continue this research with the potential to raise the bar for what AI can help us achieve. Academic proposals are expected to be submitted by May 25th and among them we will select the best research teams.

We began this journey with research into neuromorphic computing – focusing on our understanding of the human brain and its associated computational processes. The start of the neuromorphic research community announced on March 1 is also on track and we are planning to continue to scale up our Loihi on the cloud to allow researchers access to cutting-edge hardware. We see a path to reach 100 billion synapses on a single system in 2019.

Furthermore, Intel has already been working to decode the brain and advance the next stage in neuroscience as part of our research partnership with Princeton University. We are looking forward to further understanding the flow of intelligence and decision-making through our probabilistic computing work. [20]

## Deep learning comes full circle

For years, the people developing artificial intelligence drew inspiration from what was known about the human brain, and it has enjoyed a lot of success as a result. Now, AI is starting to return the favor.

Although not explicitly designed to do so, certain artificial intelligence systems seem to mimic our brains' inner workings more closely than previously thought, suggesting that both AI and our minds have converged on the same approach to solving problems. If so, simply watching AI at work could help researchers unlock some of the deepest mysteries of the [brain](#).

"There's a real connection there," said Daniel Yamins, assistant professor of psychology. Now, Yamins, who is also a faculty scholar of the Stanford Neurosciences Institute and a member of Stanford Bio-X, and his lab are building on that connection to produce better theories of the brain – how it perceives the world, how it shifts efficiently from one task to the next and perhaps, one day, how it thinks.

## A vision problem for AI

Artificial intelligence has been borrowing from the brain since its early days, when computer scientists and psychologists developed algorithms called neural networks that loosely mimicked the brain. Those algorithms were frequently criticized for being biologically implausible – the "neurons" in neural networks were, after all, gross simplifications of the real neurons that make up the brain. But computer scientists didn't care about biological plausibility. They just wanted systems that worked, so they extended neural network models in whatever way made the algorithm best able to carry out certain tasks, culminating in what is now called [deep learning](#).

Then came a surprise. In 2012, AI researchers showed that a deep learning neural network could learn to identify objects in pictures as well as a human being, which got neuroscientists wondering: How did deep learning do it?

The same way the brain does, as it turns out. In 2014, Yamins and colleagues showed that a deep learning system that had learned to identify objects in pictures – nearly as well as humans could – did so in a way that closely mimicked the way the brain processes vision. In fact, the computations

the deep learning system performed matched activity in the brain's vision-processing circuits substantially better than any other model of those circuits.

Around the same time, other teams made similar observations about parts of the brain's vision- and movement-processing circuits, suggesting that given the same kind of problem, deep learning and the brain had evolved similar ways of coming up with a solution. More recently, Yamins and colleagues have demonstrated similar observations in the brain's auditory system.

On one hand, that's not a big surprise. Although the technical details differ, deep learning's conceptual organization is borrowed directly from what neuroscientists already knew about the organization of neurons in the brain.

But the success of Yamins and colleagues' approach and others like it depends equally as much on another, more subtle choice. Rather than try to get the deep learning system to directly match what the brain does at the level of individual neurons, as many researchers had done, Yamins and colleagues simply gave their deep learning system the same problem: Identify objects in pictures. Only after it had solved that problem did the researchers compare how deep learning and the brain arrived at their solutions – and only then did it become clear that their methods were essentially the same.

"The correspondence between the models and the visual system is not entirely a coincidence, because one directly inspired the other," said Daniel Bear, a postdoctoral researcher in Yamins' group, "but it's still remarkable that it's as good a correspondence as it is."

One likely reason for that, Bear said, is natural selection and evolution. "Basically, object recognition was a very evolutionarily important task" for animals to solve – and solve well, if they wanted to tell the difference between something they could eat and something that could eat them. Perhaps trying to do that as well as humans and other animals do – except with a computer – led researchers to find essentially the same solution.

### **Seek what the brain seeks**

Whatever the underlying reason, insights gleaned from the 2014 study led to what Yamins calls goal-directed models of the brain: Rather than try to model neural activity in the brain directly, instead train artificial intelligence to solve problems the brain needs to solve, then use the resulting AI system as a model of the brain. Since 2014, Yamins and collaborators have been refining the original goal-directed model of the brain's vision circuits and extending the work in new directions, including understanding the neural circuits that process inputs from rodents' whiskers.

In perhaps the most ambitious project, Yamins and postdoctoral fellow Nick Haber are investigating how infants learn about the world around them through play. Their infants – actually relatively simple computer simulations – are motivated only by curiosity. They explore their worlds by moving around and interacting with objects, learning as they go to predict what happens when they hit balls or simply turn their heads. At the same time, the model learns to predict what parts of the world it doesn't understand, then tries to figure those out.

While the computer simulation begins life – so to speak – knowing essentially nothing about the world, it eventually figures out how to categorize different objects and even how to smash two or three of them together. Although direct comparisons with babies' neural activity might be

premature, the model could help researchers better understand how infants use play to learn about their environments, Haber said.

On the other end of the spectrum, models inspired by artificial intelligence could help solve a puzzle about the physical layout of the brain, said Eshed Margalit, a graduate student in neurosciences. As the vision circuits in infants' brains develop, they form specific patches – physical clusters of neurons – that respond to different kinds of objects. For example, humans and other primates all form a face patch that is active almost exclusively when they look at faces.

Exactly why the brain forms those patches, Margalit said, isn't clear. The brain doesn't need a face patch to recognize faces, for example. But by building on AI models like Yamins' that already solve object recognition tasks, "we can now try to model that spatial structure and ask questions about why the brain is laid out this way and what advantages it might give an organism," Margalit said.

### Closing the loop

There are other issues to tackle as well, notably how artificial intelligence systems learn. Right now, AI needs much more training – and much more explicit training – than humans do in order to perform as well on tasks like object recognition, although how humans succeed with so little data remains unclear.

A second issue is how to go beyond models of vision and other sensory systems. "Once you have a sensory impression of the world, you want to make decisions based on it," Yamins said. "We're trying to make models of decision making, learning to make decisions and how you interface between sensory systems, decision making and memory." Yamins is starting to address those ideas with Kevin Feiglis, a graduate student in physics, who is building AI models that can learn to solve many different kinds of problems and switch between tasks as needed, something very few AI systems are able to do.

In the long run, Yamins and the other members of his group said all of those advances could feed into more capable artificial intelligence systems, just as earlier neuroscience research helped foster the development of deep learning. "I think people in artificial intelligence are realizing there are certain very good next goals for cognitively inspired artificial intelligence," Haber said, including systems like his that learn by actively exploring their worlds. "People are playing with these ideas." [19]

## Scientists pioneer use of deep learning for real-time gravitational wave discovery

Scientists at the National Center for Supercomputing Applications (NCSA), located at the University of Illinois at Urbana-Champaign, have pioneered the use of GPU-accelerated deep learning for rapid detection and characterization of gravitational waves. This new approach will enable astronomers to study gravitational waves using minimal computational resources, reducing time to discovery and



increasing the scientific reach of gravitational wave astrophysics. This innovative research was recently published in *Physics Letters B*.

Combining deep learning algorithms, numerical relativity simulations of black hole mergers—obtained with the Einstein Toolkit run on the Blue Waters supercomputer—and data from the LIGO Open Science Center, NCSA Gravity Group researchers Daniel George and Eliu Huerta produced Deep Filtering, an end-to-end time-series signal processing method. Deep Filtering achieves similar sensitivities and lower errors compared to established [gravitational wave detection](#) algorithms, while being far more computationally efficient and more resilient to noise anomalies. The method allows faster than real-time processing of [gravitational waves](#) in LIGO's raw data, and also enables new physics, since it can detect new classes of gravitational wave sources that may go unnoticed with existing detection algorithms. George and Huerta are extending this method to identify in real-time electromagnetic counterparts to gravitational wave events in future LSST data.

NCSA's Gravity Group leveraged NCSA resources from its Innovative Systems Laboratory, NCSA's Blue Waters supercomputer, and collaborated with talented interdisciplinary staff at the University of Illinois. Also critical to this research were the GPUs (Tesla P100 and DGX-1) provided by NVIDIA, which enabled an accelerated training of neural networks. Wolfram Research also played an important role, as the Wolfram Language was used in creating this framework for deep learning.

George and Huerta worked with NVIDIA and Wolfram researchers to create this demo to visualize the architecture of Deep Filtering, and to get insights into its neuronal activity during the detection and characterization of real gravitational wave events. This demo highlights all the components of Deep Filtering, exhibiting its detection sensitivity and computational performance. [18]

## Mathematicians develop model for how new ideas emerge

Researchers from Queen Mary University of London have developed a mathematical model for the emergence of innovations.

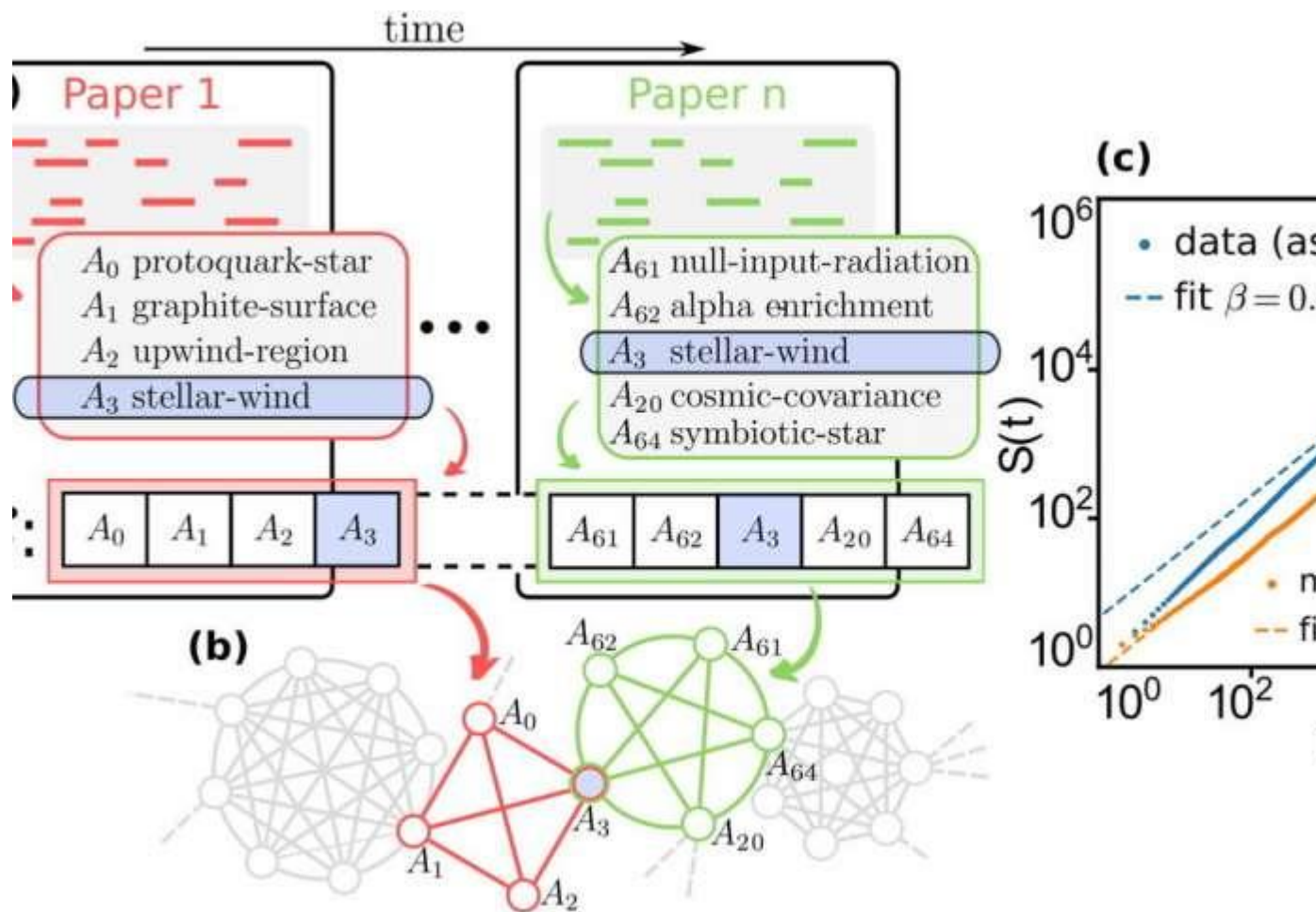
Studying creative processes and understanding how innovations arise and how novelties can trigger further discoveries could lead to effective interventions to nurture the success and sustainable growth of society.

Empirical findings have shown that the way in which novelties are discovered follows similar patterns in a variety of different contexts including science, arts, and technology.

The study, published in *Physical Review Letters*, introduces a new mathematical framework that correctly reproduces the rate at which novelties emerge in real systems, known as Heaps' law, and can explain why discoveries are strongly correlated and often come in clusters.

It does this by translating the theory of the 'adjacent possible', initially formulated by Stuart Kauffman in the context of biological systems, into the language of complex networks. The adjacent possible is the set of all novel opportunities that open up when a [new discovery](#) is made. Networks have emerged as a powerful way to both investigate real world systems, by capturing the essential

relations between the components, and to model the hidden structure behind many complex social phenomena.



Growth of knowledge in science. (a) An empirical sequence of scientific concepts  $S$  is extracted from a temporally ordered sequence of papers by concatenating, for each scientific field, the relevant concepts present in the abstracts. (b) ...[more](#)

In this work, networks are used to model the underlying space of relations among concepts.

Lead author Professor Vito Latora, from Queen Mary's School of Mathematical Sciences, said: "This research opens up new directions for the modelling of innovation, together with a new framework that could become important in the investigation of technological, biological, artistic, and commercial systems."

He added: "Studying the processes through which innovations arise can help understanding the main ingredients behind a winning idea, a breakthrough technology or a successful commercial activity, and is fundamental to devise effective data-informed decisions, strategies, and interventions to nurture the success and sustainable growth of our society."

In the study, the discovery process is modelled as a particular class of random walks, named 'reinforced' walks, on an underlying network of relations among concepts and ideas. An innovation

corresponds to the first visit of a site of the network, and every time a walker moves from a concept to another, such association (an edge in the network) is reinforced so that it will be used more frequently in the future. The researchers named this the 'edge-reinforced random walk' model.

To show how the model works in a real case, they also constructed a dataset of 20 years of scientific publications in different disciplines, such as astronomy, ecology, economics and mathematics to analyse the appearance of new concepts. This showed that, despite its simplicity, the edge-reinforced random walk model is able to reproduce how knowledge grows in modern science.

Professor Vito Latora added: "The framework we present constitutes a new approach for the study of discovery processes, in particular those for which the underlying network can be directly reconstructed from empirical data, for example users listening to music over a similarity network between songs. We are already working on this idea, together with an extended version of our model, where we study the collective exploration of these networked spaces by considering multiple walkers at the same time." [17]

## Rise of the quantum thinking machines

Quantum computers can be made to utilize effects such as quantum coherence and entanglement to accelerate machine learning.

Although we typically view information as being an abstract or virtual entity, information, of course, must be stored in a physical medium. Information processing devices such as computers and phones are therefore fundamentally governed by the laws of physics. In this way, the fundamental physical limits of an agent's ability to learn are governed by the laws of physics. The best known theory of physics is quantum theory, which ultimately must be used to determine the absolute physical limits of a machine's ability to learn.

A quantum algorithm is a stepwise procedure performed on a quantum computer to solve a problem such as searching a database. Quantum machine learning software makes use of quantum algorithms to process information in ways that classical computers cannot. These quantum effects open up exciting new avenues which can, in principle, outperform the best known classical algorithms when solving certain machine learning problems. This is known as quantum enhanced machine learning.

Machine learning methods use mathematical algorithms to search for certain patterns in large data sets. Machine learning is widely used in biotechnology, pharmaceuticals, particle physics and many other fields. Thanks to the ability to adapt to new data, machine learning greatly exceeds the ability of people. Despite this, machine learning cannot cope with certain difficult tasks.

Quantum enhancement is predicted to be possible for a host of machine learning tasks, ranging from optimization to quantum enhanced deep learning.

In the new paper published in Nature, a group of scientists led by Skoltech Associate Professor Jacob Biamonte produced a feasibility analysis outlining what steps can be taken for practical quantum enhanced machine learning.

The prospects of using quantum computers to accelerate machine learning has generated recent excitement due to the increasing capabilities of quantum computers. This includes a commercially available 2000 spin quantum accelerated annealing by the Canada-based company D-Wave Systems Inc. and a 16 qubit universal quantum processor by IBM which is accessible via a (currently free) cloud service.

The availability of these devices has led to increased interest from the machine learning community. The interest comes as a bit of a shock to the traditional quantum physics community, in which researchers have thought that the primary applications of quantum computers would be using quantum computers to simulate chemical physics, which can be used in the pharmaceutical industry for drug discovery. However, certain quantum systems can be mapped to certain machine learning models, particularly deep learning models. Quantum machine learning can be used to work in tandem with these existing methods for quantum chemical emulation, leading to even greater capabilities for a new era of quantum technology.

"Early on, the team burned the midnight oil over Skype, debating what the field even was—our synthesis will hopefully solidify topical importance. We submitted our draft to Nature, going forward subject to significant changes. All in all, we ended up writing three versions over eight months with nothing more than the title in common," said lead study author Biamonte. [16]

## **A Machine Learning Systems That Called Neural Networks Perform Tasks by Analyzing Huge Volumes of Data**

Neural networks learn how to carry out certain tasks by analyzing large amounts of data displayed to them. These machine learning systems continually learn and readjust to be able to carry out the task set out before them. Understanding how neural networks work helps researchers to develop better applications and uses for them.

At the 2017 Conference on Empirical Methods on Natural Language Processing earlier this month, MIT researchers demonstrated a new general-purpose technique for making sense of neural networks that are able to carry out natural language processing tasks where they attempt to extract data written in normal text opposed to something of a structured language like database-query language.

The new technique works great in any system that reads the text as input and produces symbols as the output. One such example of this can be seen in an automatic translator. It works without the need to access any underlying software too. Tommi Jaakkola is Professor of Electrical Engineering and Computer Science at MIT and one of the authors on the paper. He says, "I can't just do a simple randomization. And what you are predicting is now a more complex object, like a sentence, so what does it mean to give an explanation?"

As part of the research, Jaakkola, and colleague David Alvarez-Melis, an MIT graduate student in electrical engineering and computer science and first author on the paper, used a black-box neural

net in which to generate test sentences to feed black-box neural nets. The duo began by teaching the network to compress and decompress natural sentences. As the training continues the encoder and decoder get evaluated simultaneously depending on how closely the decoder's output matches up with the encoder's input.

Neural nets work on probabilities. For example, an object-recognition system could be fed an image of a cat, and it would process that image as it saying 75 percent probability of being a cat, while still having a 25 percent probability that it's a dog. Along with that same line, Jaakkola and Alvarez-Melis' sentence compressing network has alternative words for each of those in a decoded sentence along with the probability that each is correct. So, once the system has generated a list of closely related sentences they're then fed to a black-box natural language processor. This then allows the researchers to analyze and determine which inputs have an effect on which outputs.

During the research, the pair applied this technique to three different types of a natural language processing system. The first one inferred the way in which words were pronounced; the second was a set of translators, and the third was a simple computer dialogue system which tried to provide adequate responses to questions or remarks. In looking at the results, it was clear and pretty obvious that the translation systems had strong dependencies on individual words of both the input and output sentences. A little more surprising, however, was the identification of gender biases in the texts on which the machine translation systems were trained. The dialogue system was too small to take advantage of the training set.

"The other experiment we do is in flawed systems," says Alvarez-Melis. "If you have a black-box model that is not doing a good job, can you first use this kind of approach to identify problems? A motivating application of this kind of interpretability is to fix systems, to improve systems, by understanding what they're getting wrong and why." [15]

## **Active machine learning for the discovery and crystallization of gigantic polyoxometalate molecules**

Who is the better experimentalist, a human or a robot? When it comes to exploring synthetic and crystallization conditions for inorganic gigantic molecules, actively learning machines are clearly ahead, as demonstrated by British Scientists in an experiment with polyoxometalates published in the journal *Angewandte Chemie*.

Polyoxometalates form through self-assembly of a large number of metal atoms bridged by oxygen atoms. Potential uses include catalysis, electronics, and medicine. Insights into the self-organization processes could also be of use in developing functional chemical systems like "molecular machines".

Polyoxometalates offer a nearly unlimited variety of structures. However, it is not easy to find new ones, because the aggregation of complex inorganic molecules to gigantic molecules is a process that is difficult to predict. It is necessary to find conditions under which the building blocks aggregate and then also crystallize, so that they can be characterized.

A team led by Leroy Cronin at the University of Glasgow (UK) has now developed a new approach to define the range of suitable conditions for the synthesis and crystallization of polyoxometalates.

It is based on recent advances in machine learning, known as active learning. They allowed their trained machine to compete against the intuition of experienced experimenters. The test example was  $\text{Na}_6[\text{Mo}_{120}\text{Ce}_6\text{O}_{366}\text{H}_{12}(\text{H}_2\text{O})_{78}]\cdot 200 \text{H}_2\text{O}$ , a new, ring-shaped polyoxometalate cluster that was recently discovered by the researchers' automated chemical robot.

In the experiment, the relative quantities of the three necessary reagent solutions were to be varied while the protocol was otherwise prescribed. The starting point was a set of data from successful and unsuccessful crystallization experiments. The aim was to plan ten experiments and then use the results from these to proceed to the next set of ten experiments - a total of one hundred crystallization attempts.

Although the flesh-and-blood experimenters were able to produce more successful crystallizations, the far more "adventurous" machine algorithm was superior on balance because it covered a significantly broader domain of the "crystallization space". The quality of the prediction of whether an experiment would lead to crystallization was improved significantly more by the machine than the human experimenters. A series of 100 purely random experiments resulted in no improvement. In addition, the machine discovered a range of conditions that led to crystals which would not have been expected based on pure intuition. This "unbiased" automated method makes the discovery of novel compounds more probably than reliance on human intuition. The researchers are now looking for ways to make especially efficient "teams" of man and machine. [14]

## Using machine learning to understand materials

Whether you realize it or not, machine learning is making your online experience more efficient. The technology, designed by computer scientists, is used to better understand, analyze, and categorize data. When you tag your friend on Facebook, clear your spam filter, or click on a suggested YouTube video, you're benefitting from machine learning algorithms.

Machine learning algorithms are designed to improve as they encounter more data, making them a versatile technology for understanding large sets of photos such as those accessible from Google Images. Elizabeth Holm, professor of materials science and engineering at Carnegie Mellon University, is leveraging this technology to better understand the enormous number of research images accumulated in the field of materials science. This unique application is an interdisciplinary approach to machine learning that hasn't been explored before.

"Just like you might search for cute cat pictures on the internet, or Facebook recognizes the faces of your friends, we are creating a system that allows a computer to automatically understand the visual data of materials science," explains Holm.

The field of materials science usually relies on human experts to identify research images by hand. Using machine learning algorithms, Holm and her group have created a system that automatically recognizes and categorizes microstructural images of materials. Her goal is to make it more efficient for materials scientists to search, sort, classify, and identify important information in their visual data.

"In materials science, one of our fundamental data is pictures," explains Holm. "Images contain information that we recognize, even when we find it difficult to quantify numerically."

Holm's machine learning system has several different applications within the materials science field including research, industry, publishing, and academia. For example, the system could be used to create a visual search of a scientific journal archives so that a researcher could find out whether a similar image had ever been published. Similarly, the system can be used to automatically search and categorize image archives in industries or research labs. "Big companies can have archives of 600,000 or more research images. No one wants to look through those, but they want to use that data to better understand their products," explains Holm. "This system has the power to unlock those archives."

Holm and her group have been working on this research for about three years and are continuing to grow the project, especially as it relates to the metal 3-D printing field. For example, they are beginning to compile a database of experimental and simulated metal powder micrographs in order to better understand what types of raw materials are best suited for 3-D printing processes.

Holm published an article about this research in the December 2015 issue of Computational Materials Science titled "A computer vision approach for automated analysis and classification of microstructural image data." [13]

## **Artificial intelligence helps in the discovery of new materials**

With the help of artificial intelligence, chemists from the University of Basel in Switzerland have computed the characteristics of about two million crystals made up of four chemical elements. The researchers were able to identify 90 previously unknown thermodynamically stable crystals that can be regarded as new materials.

They report on their findings in the scientific journal Physical Review Letters.

Elpasolite is a glassy, transparent, shiny and soft mineral with a cubic crystal structure. First discovered in El Paso County (Colorado, USA), it can also be found in the Rocky Mountains, Virginia and the Apennines (Italy). In experimental databases, elpasolite is one of the most frequently found quaternary crystals (crystals made up of four chemical elements). Depending on its composition, it can be a metallic conductor, a semi-conductor or an insulator, and may also emit light when exposed to radiation.

These characteristics make elpasolite an interesting candidate for use in scintillators (certain aspects of which can already be demonstrated) and other applications. Its chemical complexity means that, mathematically speaking, it is practically impossible to use quantum mechanics to predict every theoretically viable combination of the four elements in the structure of elpasolite.

## **Machine learning aids statistical analysis**

Thanks to modern artificial intelligence, Felix Faber, a doctoral student in Prof. Anatole von Lilienfeld's group at the University of Basel's Department of Chemistry, has now succeeded in solving this material design problem. First, using quantum mechanics, he generated predictions for thousands of elpasolite crystals with randomly determined chemical compositions. He then used the results to train statistical machine learning models (ML models). The improved algorithmic strategy achieved a predictive accuracy equivalent to that of standard quantum mechanical approaches.

ML models have the advantage of being several orders of magnitude quicker than corresponding quantum mechanical calculations. Within a day, the ML model was able to predict the formation energy – an indicator of chemical stability – of all two million elpasolite crystals that theoretically can be obtained from the main group elements of the periodic table. In contrast, performance of the calculations by quantum mechanical means would have taken a supercomputer more than 20 million hours.

### **Unknown materials with interesting characteristics**

An analysis of the characteristics computed by the model offers new insights into this class of materials. The researchers were able to detect basic trends in formation energy and identify 90 previously unknown crystals that should be thermodynamically stable, according to quantum mechanical predictions.

On the basis of these potential characteristics, elpasolite has been entered into the Materials Project material database, which plays a key role in the Materials Genome Initiative. The initiative was launched by the US government in 2011 with the aim of using computational support to accelerate the discovery and the experimental synthesis of interesting new materials.

Some of the newly discovered elpasolite crystals display exotic electronic characteristics and unusual compositions. "The combination of artificial intelligence, big data, quantum mechanics and supercomputing opens up promising new avenues for deepening our understanding of materials and discovering new ones that we would not consider if we relied solely on human intuition," says study director von Lilienfeld. [12]

### **Physicists are putting themselves out of a job, using artificial intelligence to run a complex experiment**

The experiment, developed by physicists from The Australian National University (ANU) and UNSW ADFA, created an extremely cold gas trapped in a laser beam, known as a Bose-Einstein condensate, replicating the experiment that won the 2001 Nobel Prize.

"I didn't expect the machine could learn to do the experiment itself, from scratch, in under an hour," said co-lead researcher Paul Wigley from the ANU Research School of Physics and Engineering.

"A simple computer program would have taken longer than the age of the Universe to run through all the combinations and work this out."

Bose-Einstein condensates are some of the coldest places in the Universe, far colder than outer space, typically less than a billionth of a degree above absolute zero.

They could be used for mineral exploration or navigation systems as they are extremely sensitive to external disturbances, which allows them to make very precise measurements such as tiny changes in the Earth's magnetic field or gravity.

The artificial intelligence system's ability to set itself up quickly every morning and compensate for any overnight fluctuations would make this fragile technology much more useful for field measurements, said co-lead researcher Dr Michael Hush from UNSW ADFA.



"You could make a working device to measure gravity that you could take in the back of a car, and the artificial intelligence would recalibrate and fix itself no matter what," he said.

"It's cheaper than taking a physicist everywhere with you."

The team cooled the gas to around 1 microkelvin, and then handed control of the three laser beams over to the artificial intelligence to cool the trapped gas down to nanokelvin.

Researchers were surprised by the methods the system came up with to ramp down the power of the lasers.

"It did things a person wouldn't guess, such as changing one laser's power up and down, and compensating with another," said Mr Wigley.

"It may be able to come up with complicated ways humans haven't thought of to get experiments colder and make measurements more precise.

The new technique will lead to bigger and better experiments, said Dr Hush.

"Next we plan to employ the artificial intelligence to build an even larger Bose-Einstein condensate faster than we've seen ever before," he said.

The research is published in the Nature group journal Scientific Reports. [11]

## **Quantum experiments designed by machines**

The idea was developed when the physicists wanted to create new quantum states in the laboratory, but were unable to conceive of methods to do so. "After many unsuccessful attempts to come up with an experimental implementation, we came to the conclusion that our intuition about these phenomena seems to be wrong. We realized that in the end we were just trying random arrangements of quantum building blocks. And that is what a computer can do as well - but thousands of times faster", explains Mario Krenn, PhD student in Anton Zeilinger's group and first author research.

After a few hours of calculation, their algorithm - which they call Melvin - found the recipe to the question they were unable to solve, and its structure surprised them. Zeilinger says: "Suppose I want build an experiment realizing a specific quantum state I am interested in. Then humans intuitively consider setups reflecting the symmetries of the state. Yet Melvin found out that the most simple realization can be asymmetric and therefore counterintuitive. A human would probably never come up with that solution."

The physicists applied the idea to several other questions and got dozens of new and surprising answers. "The solutions are difficult to understand, but we were able to extract some new experimental tricks we have not thought of before. Some of these computer-designed experiments are being built at the moment in our laboratories", says Krenn.

Melvin not only tries random arrangements of experimental components, but also learns from previous successful attempts, which significantly speeds up the discovery rate for more complex

solutions. In the future, the authors want to apply their algorithm to even more general questions in quantum physics, and hope it helps to investigate new phenomena in laboratories. [10]

## **Moving electrons around loops with light: A quantum device based on geometry**

Researchers at the University of Chicago's Institute for Molecular Engineering and the University of Konstanz have demonstrated the ability to generate a quantum logic operation, or rotation of the qubit, that - surprisingly—is intrinsically resilient to noise as well as to variations in the strength or duration of the control. Their achievement is based on a geometric concept known as the Berry phase and is implemented through entirely optical means within a single electronic spin in diamond.

Their findings were published online Feb. 15, 2016, in *Nature Photonics* and will appear in the March print issue. "We tend to view quantum operations as very fragile and susceptible to noise, especially when compared to conventional electronics," remarked David Awschalom, the Liew Family Professor of Molecular Engineering and senior scientist at Argonne National Laboratory, who led the research. "In contrast, our approach shows incredible resilience to external influences and fulfills a key requirement for any practical quantum technology."

### **Quantum geometry**

When a quantum mechanical object, such as an electron, is cycled along some loop, it retains a memory of the path that it travelled, the Berry phase. To better understand this concept, the Foucault pendulum, a common staple of science museums helps to give some intuition. A pendulum, like those in a grandfather clock, typically oscillates back and forth within a fixed plane. However, a Foucault pendulum oscillates along a plane that gradually rotates over the course of a day due to Earth's rotation, and in turn knocks over a series of pins encircling the pendulum.

The number of knocked-over pins is a direct measure of the total angular shift of the pendulum's oscillation plane, its acquired geometric phase. Essentially, this shift is directly related to the location of the pendulum on Earth's surface as the rotation of Earth transports the pendulum along a specific closed path, its circle of latitude. While this angular shift depends on the particular path traveled, Awschalom said, it remarkably does not depend on the rotational speed of Earth or the oscillation frequency of the pendulum.

"Likewise, the Berry phase is a similar path-dependent rotation of the internal state of a quantum system, and it shows promise in quantum information processing as a robust means to manipulate qubit states," he said.

### **A light touch**

In this experiment, the researchers manipulated the Berry phase of a quantum state within a nitrogen-vacancy (NV) center, an atomic-scale defect in diamond. Over the past decade and a half, its electronic spin state has garnered great interest as a potential qubit. In their experiments, the team members developed a method with which to draw paths for this defect's spin by varying the applied laser light. To demonstrate Berry phase, they traced loops similar to that of a tangerine slice within the quantum space of all of the potential combinations of spin states.

"Essentially, the area of the tangerine slice's peel that we drew dictated the amount of Berry phase that we were able to accumulate," said Christopher Yale, a postdoctoral scholar in Awschalom's laboratory, and one of the co-lead authors of the project.

This approach using laser light to fully control the path of the electronic spin is in contrast to more common techniques that control the NV center spin, through the application of microwave fields. Such an approach may one day be useful in developing photonic networks of these defects, linked and controlled entirely by light, as a way to both process and transmit quantum information.

### **A noisy path**

A key feature of Berry phase that makes it a robust quantum logic operation is its resilience to noise sources. To test the robustness of their Berry phase operations, the researchers intentionally added noise to the laser light controlling the path. As a result, the spin state would travel along its intended path in an erratic fashion.

However, as long as the total area of the path remained the same, so did the Berry phase that they measured.

"In particular, we found the Berry phase to be insensitive to fluctuations in the intensity of the laser. Noise like this is normally a bane for quantum control," said Brian Zhou, a postdoctoral scholar in the group, and co-lead author.

"Imagine you're hiking along the shore of a lake, and even though you continually leave the path to go take pictures, you eventually finish hiking around the lake," said F. Joseph Heremans, co-lead author, and now a staff scientist at Argonne National Laboratory. "You've still hiked the entire loop regardless of the bizarre path you took, and so the area enclosed remains virtually the same."

These optically controlled Berry phases within diamond suggest a route toward robust and fault-tolerant quantum information processing, noted Guido Burkard, professor of physics at the University of Konstanz and theory collaborator on the project.

"Though its technological applications are still nascent, Berry phases have a rich underlying mathematical framework that makes them a fascinating area of study," Burkard said. [9]

### **Researchers demonstrate 'quantum surrealism'**

In a new version of an old experiment, CIFAR Senior Fellow Aephraim Steinberg (University of Toronto) and colleagues tracked the trajectories of photons as the particles traced a path through one of two slits and onto a screen. But the researchers went further, and observed the "nonlocal" influence of another photon that the first photon had been entangled with.

The results counter a long-standing criticism of an interpretation of quantum mechanics called the De Broglie-Bohm theory. Detractors of this interpretation had faulted it for failing to explain the behaviour of entangled photons realistically. For Steinberg, the results are important because they give us a way of visualizing quantum mechanics that's just as valid as the standard interpretation, and perhaps more intuitive.

"I'm less interested in focusing on the philosophical question of what's 'really' out there. I think the fruitful question is more down to earth. Rather than thinking about different metaphysical

interpretations, I would phrase it in terms of having different pictures. Different pictures can be useful. They can help shape better intuitions."

At stake is what is "really" happening at the quantum level. The uncertainty principle tells us that we can never know both a particle's position and momentum with complete certainty. And when we do interact with a quantum system, for instance by measuring it, we disturb the system. So if we fire a photon at a screen and want to know where it will hit, we'll never know for sure exactly where it will hit or what path it will take to get there.

The standard interpretation of quantum mechanics holds that this uncertainty means that there is no "real" trajectory between the light source and the screen. The best we can do is to calculate a "wave function" that shows the odds of the photon being in any one place at any time, but won't tell us where it is until we make a measurement.

Yet another interpretation, called the De Broglie-Bohm theory, says that the photons do have real trajectories that are guided by a "pilot wave" that accompanies the particle. The wave is still probabilistic, but the particle takes a real trajectory from source to target. It doesn't simply "collapse" into a particular location once it's measured.

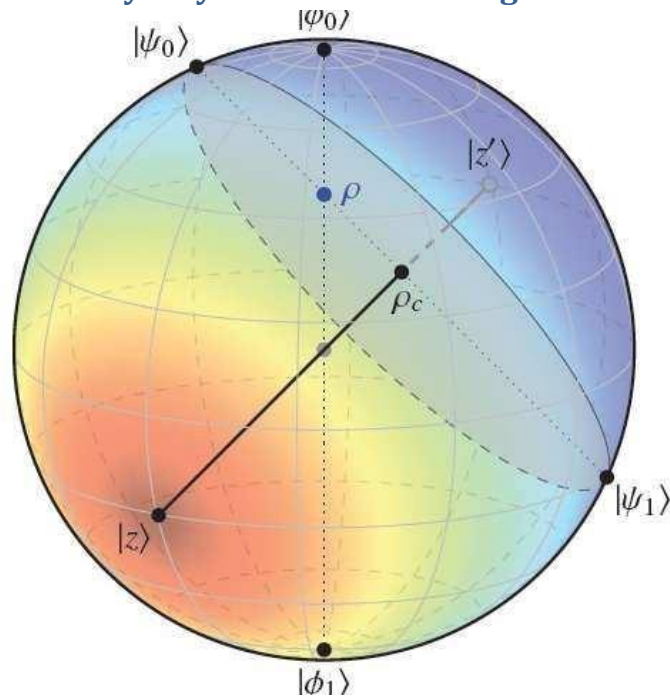
In 2011 Steinberg and his colleagues showed that they could follow trajectories for photons by subjecting many identical particles to measurements so weak that the particles were barely disturbed, and then averaging out the information. This method showed trajectories that looked similar to classical ones - say, those of balls flying through the air.

But critics had pointed out a problem with this viewpoint. Quantum mechanics also tells us that two particles can be entangled, so that a measurement of one particle affects the other. The critics complained that in some cases, a measurement of one particle would lead to an incorrect prediction of the trajectory of the entangled particle. They coined the term "surreal trajectories" to describe them.

In the most recent experiment, Steinberg and colleagues showed that the surrealism was a consequence of non-locality - the fact that the particles were able to influence one another instantaneously at a distance. In fact, the "incorrect" predictions of trajectories by the entangled photon were actually a consequence of where in their course the entangled particles were measured. Considering both particles together, the measurements made sense and were consistent with real trajectories.

Steinberg points out that both the standard interpretation of quantum mechanics and the De Broglie-Bohm interpretation are consistent with experimental evidence, and are mathematically equivalent. But it is helpful in some circumstances to visualize real trajectories, rather than wave function collapses, he says. [8]

## Physicists discover easy way to measure entanglement—on a sphere



Entanglement on a sphere: This Bloch sphere shows entanglement for the one-root state  $\rho$  and its radial state  $\rho_c$ . The color on the sphere corresponds to the value of the entanglement, which is determined by the distance from the root state  $z$ , the point at which there is no entanglement (red); the further from  $z$ , the greater the entanglement (blue). Credit: Regula and Adesso. ©2016 American Physical Society

Now in a new paper to be published in *Physical Review Letters*, mathematical physicists Bartosz Regula and Gerardo Adesso at The University of Nottingham have greatly simplified the problem of measuring entanglement.

To do this, the scientists turned the difficult analytical problem into an easy geometrical one. They showed that, in many cases, the amount of entanglement between states corresponds to the distance between two points on a Bloch sphere, which is basically a normal 3D sphere that physicists use to model quantum states.

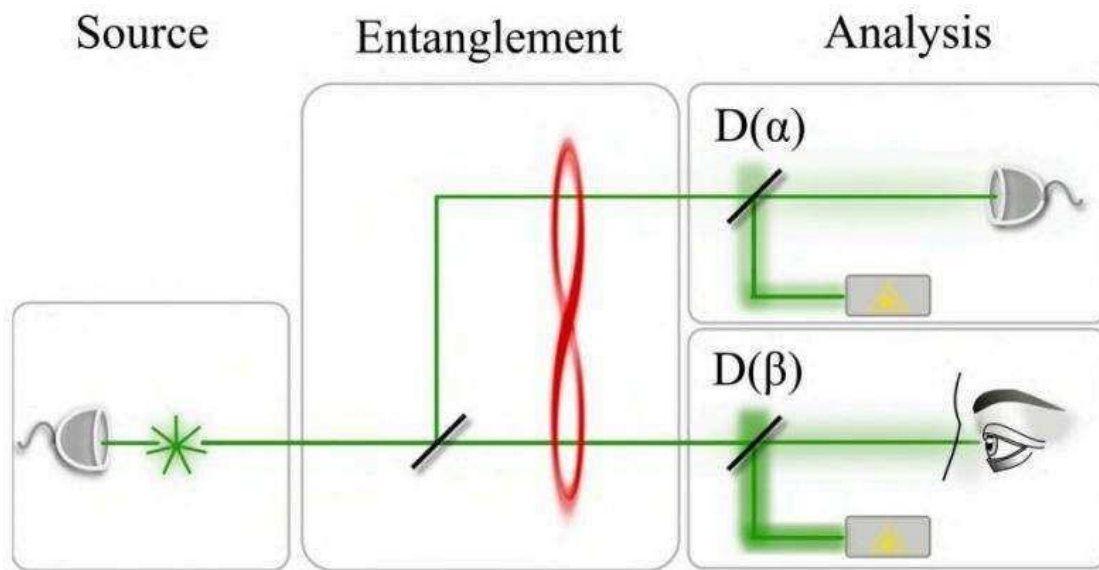
As the scientists explain, the traditionally difficult part of the math problem is that it requires finding the optimal decomposition of mixed states into pure states. The geometrical approach completely eliminates this requirement by reducing the many possible ways that states could decompose down to a single point on the sphere at which there is zero entanglement. The approach requires that there be only one such point, or "root," of zero entanglement, prompting the physicists to describe the method as "one root to rule them all."

The scientists explain that the "one root" property is common among quantum states and can be easily verified, transforming a formidable math problem into one that is trivially easy. They demonstrated that the new approach works for many types of two-, three- and four-qubit entangled states.

"This method reveals an intriguing and previously unexplored connection between the quantum features of a state and classical geometry, allowing all one-root states to enjoy a convenient visual representation which considerably simplifies the study and understanding of their properties," the researchers explained.

The simple way of measuring a state's entanglement could have applications in many technological areas, such as quantum cryptography, computation, and communication. It could also provide insight into understanding the foundations of thermodynamics, condensed matter physics, and biology. [7]

### An idea for allowing the human eye to observe an instance of entanglement



Scheme of the proposal for detecting entanglement with the human eye. Credit: arXiv:1602.01907

Entanglement, is of course, where two quantum particles are intrinsically linked to the extent that they actually share the same existence, even though they can be separated and moved apart. The idea was first proposed nearly a century ago, and it has not only been proven, but researchers routinely cause it to occur, but, to date, not one single person has ever actually seen it happen—they only know it happens by conducting a series of experiments. It is not clear if anyone has ever actually tried to see it happen, but in this new effort, the research trio claim to have found a way to make it happen—if only someone else will carry out the experiment on a willing volunteer.

The idea involves using a beam splitter and two beams of light—an initial beam of coherent photons fired at the beam splitter and a secondary beam of coherent photons that interferes with the photons in the first beam causing a change of phase, forcing the light to be reflected rather than transmitted. In such a scenario, the secondary beam would not need to be as intense as the first, and could in fact be just a single coherent photon—if it were entangled, it could be used to allow a person to see the more powerful beam while still preserving the entanglement of the original photon.

The researchers suggest the technology to carry out such an experiment exists today, but also acknowledge that it would take a special person to volunteer for such an assignment because to prove that they had seen entanglement taking place would involve shooting a large number of photons in series, into a person's eye, whereby the resolute volunteer would announce whether they had seen the light on the order of thousands of times. [6]

## Quantum entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

## The Bridge

The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories. [1]

## Accelerating charges

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field. In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion. The same thing happens on the atomic scale giving a dp impulse difference and a dx way difference between the different part of the not point like particles.

## Relativistic effect

Another bridge between the classical and quantum mechanics in the realm of relativity is that the charge distribution is lowering in the reference frame of the accelerating charges linearly:  $ds/dt = at$  (time coordinate), but in the reference frame of the current it is parabolic:  $s = a/2 t^2$  (geometric coordinate).

## Heisenberg Uncertainty Relation

In the atomic scale the Heisenberg uncertainty relation gives the same result, since the moving electron in the atom accelerating in the electric field of the proton, causing a charge distribution on  $\Delta x$  position difference and with a  $\Delta p$  momentum difference such a way that their product is about the half Planck reduced constant. For the proton this  $\Delta x$  is much less in the nucleon, than in the orbit of the electron in the atom, the  $\Delta p$  is much higher because of the greater proton mass.

This means that the electron and proton are not point like particles, but have a real charge distribution.

## Wave – Particle Duality

The accelerating electrons explain the wave – particle duality of the electrons and photons, since the elementary charges are distributed on  $\Delta x$  position with  $\Delta p$  impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

## Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and its kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only that changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

## The Relativistic Bridge

Commonly accepted idea that the relativistic effect on the particle physics is the fermions' spin - another unresolved problem in the classical concepts. If the electric charges can move only with accelerated motions in the self maintaining electromagnetic field, once upon a time they would reach the velocity of the electromagnetic field. The resolution of this problem is the spinning particle, constantly accelerating and not reaching the velocity of light because the acceleration is radial. One origin of the Quantum Physics is the Planck Distribution Law of the electromagnetic oscillators, giving equal intensity for 2 different wavelengths on any temperature. Any of these two wavelengths will give equal intensity diffraction patterns, building different asymmetric constructions, for example proton - electron structures (atoms), molecules, etc. Since the particles are centers of diffraction patterns they also have particle – wave duality as the electromagnetic waves have. [2]



## The weak interaction

The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry. The Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

Another important issue of the quark model is when one quark changes its flavor such that a linear oscillation transforms into plane oscillation or vice versa, changing the charge value with 1 or -1. This kind of change in the oscillation mode requires not only parity change, but also charge and time changes (CPT symmetry) resulting a right handed anti-neutrino or a left handed neutrino.

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions, the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

The neutrino is a  $1/2$  spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with  $1/2$  spin. The weak interaction changes the entropy since more or less particles will give more or less freedom of movement. The entropy change is a result of temperature change and breaks the equality of oscillator diffraction intensity of the Maxwell–Boltzmann statistics. This way it changes the time coordinate measure and makes possible a different time dilation as of the special relativity.

The limit of the velocity of particles as the speed of light appropriate only for electrical charged particles, since the accelerated charges are self maintaining locally the accelerating electric force. The neutrinos are CP symmetry breaking particles compensated by time in the CPT symmetry, that is the time coordinate not works as in the electromagnetic interactions, consequently the speed of neutrinos is not limited by the speed of light.

The weak interaction T-asymmetry is in conjunction with the T-asymmetry of the second law of thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes the weak interaction, for example the Hydrogen fusion.

Probably because it is a spin creating movement changing linear oscillation to 2 dimensional oscillation by changing d to u quark and creating anti neutrino going back in time relative to the proton and electron created from the neutron, it seems that the anti neutrino fastest then the velocity of the photons created also in this weak interaction?

A quark flavor changing shows that it is a reflection changes movement and the CP- and T-symmetry breaking!!! This flavor changing oscillation could prove that it could be also on higher level such as atoms, molecules, probably big biological significant molecules and responsible on the aging of the life.

Important to mention that the weak interaction is always contains particles and antiparticles, where the neutrinos (antineutrinos) present the opposite side. It means by Feynman's interpretation that these particles present the backward time and probably because this they seem to move faster than the speed of light in the reference frame of the other side.

Finally since the weak interaction is an electric dipole change with  $\frac{1}{2}$  spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

## The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. A good example of this is the neutron decay, creating more particles with less known information about them.

The neutrino oscillation of the Weak Interaction shows that it is a general electric dipole change and it is possible to any other temperature dependent entropy and information changing diffraction pattern of atoms, molecules and even complicated biological living structures.

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater than subatomic matter structures as an electric dipole change. There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.

The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. So the Weak Interaction has two directions, samples for one direction is the Neutron decay, and Hydrogen fusion is the opposite direction.

## Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing.

## Van Der Waals force

Named after the Dutch scientist Johannes Diderik van der Waals – who first proposed it in 1873 to explain the behaviour of gases – it is a very weak force that only becomes relevant when atoms and molecules are very close together. Fluctuations in the electronic cloud of an atom mean that it will have an instantaneous dipole moment. This can induce a dipole moment in a nearby atom, the result being an attractive dipole–dipole interaction.

## Electromagnetic inertia and mass

### Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

### Relativistic change of mass

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

### The frequency dependence of mass

Since  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the  $m_0$  inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

### Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [2]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## Gravity from the point of view of quantum physics

### The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass ratio  $M_p=1840 M_e$ . In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have + parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

Since the Higgs boson is necessary to the W and Z bosons, the dipole change of the Weak interaction and the change in the magnetic effect caused gravitation must be conducted. The Wien law is also important to explain the Weak interaction, since it describes the  $T_{\max}$  change and the diffraction patterns change. [2]

## Higgs mechanism and Quantum Gravity

The magnetic induction creates a negative electric field, causing an electromagnetic inertia. Probably it is the mysterious Higgs field giving mass to the charged particles? We can think about the photon as an electron-positron pair, they have mass. The neutral particles are built from negative and positive charges, for example the neutron, decaying to proton and electron. The wave – particle duality makes sure that the particles are oscillating and creating magnetic induction as an inertial mass, explaining also the relativistic mass change. Higher frequency creates stronger magnetic induction, smaller frequency results lesser magnetic induction. It seems to me that the magnetic induction is the secret of the Higgs field.

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The spontaneous symmetry breaking of the underlying local symmetry triggers conversion of components of this Higgs field to Goldstone bosons which interact with (at least some of) the other fields in the theory, so as to produce mass terms for (at least some of) the gauge bosons. This mechanism may also leave behind elementary scalar (spin-0) particles, known as Higgs bosons.

In the Standard Model, the phrase "Higgs mechanism" refers specifically to the generation of masses for the  $W^\pm$ , and Z weak gauge bosons through electroweak symmetry breaking. The Large Hadron Collider at CERN announced results consistent with the Higgs particle on July 4, 2012 but stressed that further testing is needed to confirm the Standard Model.

### What is the Spin?

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particles like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

### The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests

that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [3]

## The Secret of Quantum Entanglement

The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves. [2] When one of the entangled particles wave function is collapses by measurement, the intermediate photon also collapses and transforms its state to the second entangled particle giving it the continuity of this entanglement. Since the accelerated charges are self-maintaining their potential locally causing their acceleration, it seems that they entanglement is a spooky action at a distance.

## Conclusions

The accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also.

The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves.

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. Basing the gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions.

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