Is the Honors Program There When Nobody Looks?:
Learning via Quantum Entanglement

[slide: title] Good afternoon. When Roberta asked me some months ago to give this address I went through my usual period of anticipatory, abject terror about formal public speaking engagements. As the adrenaline in my system subsided to the levels I am normally accustomed to during my waking hours, I recognized this for what it is: an opportunity to convey my love for the liberal arts and how my enthusiasm for physics fits under its umbrella. Indeed, ever since I was five years old and started kindergarten, most days I wake up feeling just like Chrysanthemum, **[slide: Chrysanthemum]** who likes her name and loves school. Hooray! School! And, yes, I am secure enough in my self-image that I can recognize the small, dress-wearing girl within myself, though the mouse part is a bit of a stretch. Whatever your self-image (and I'm not asking and I hope I haven't shared too much), it is my hope that your participation in the University Honors Program equips you with a well-made, large-diameter umbrella under which to collect your own enthusiasms.

In keeping with the awe-inspiring breadth of human knowledge, I thought at first to introduce some of the truly mind-boggling large-scale structures found in our Universe. **[slide: NGC 2841]** Then we could marvel together at how such beauty and complexity arise from just a few physical principles that can be expressed in very simple mathematical terms. About that math, the Nobel Prize-winning physicist Eugene Wigner had this to say: "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve." Although words are some of my best friends, I can't come up with such eloquence on my own in a reliable way, so I might just say something like "Space is big." **[slide: NGC 2841, big]** Which inevitably reminds me of a quote from science fiction writer Douglas Adams. **[slide: Stephan's Quintet]** "Really big." **[slide: NGC 5584]** "You may think it's a long way down the road to the chemist…" **[slide: NGC 5866]** "...but that's just peanuts to space." Peanuts indeed: go outside tonight, take a coin out of your pocket, and hold it up to the sky at arm's length. In the volume of space obscured behind the coin are about 100,000 galaxies like the ones you've seen here. Once you let that sink in for a little while, just remember "Don't Panic." [**slide: NGC 5866, don't panic]** Sound advice for galactic travelers and honors program scholars alike—you won't find all "the answers" (whatever those things are) in a single Guide, but with perseverance, flexibility of mind and a group of reliable friends I predict your intellectual journey will be a success.

At this point in my planning, my midwestern upbringing asserted itself via a desire for a more down to earth application of science and interdisciplinary learning. After all you can't eat beauty or derive nourishment from complexity. But you *can* eat a tomato. **[slide: roma theory]** What could be more useful than a theory to help gardeners, who at this time of year struggle in various ways with their harvests? Together we could build a predictive model (using simple math!) that enables the hapless tomato growers with overgrown plants and collapsed cages to efficiently **[slide: roma theory, k=1]** plan their picking sequence **[slide: roma theory, k=0.75]** and marshal the necessary tools and pilates moves **[slide: roma theory, k=0.5 et al]** to ensure a bountiful and successful harvest. **[slide: roma experiment]** In keeping with the sporting season, I treat salsa as a full-contact sport. I brought along some of my second-string salsa that I think you won't find too over-the-top. Take some home if you like it – at 72 pints so far this year I've got more than enough to share.

Finally, I settled on a topic that is neither aesthetically stunning nor mundanely practical, but one that I hope unsettles you at least a little bit: quantum entanglement. To get to the point where I can use the words “entanglement” and “honors program” together in a sentence and you experience a little *frisson* of excitement, I need to take you on a hop-skip-and-a-jump tour of some quantum theory highlights. I hope some discipline-specific illumination before the general inspiration is okay. To make a bad extension on a good metaphor, I’d like to play in the rain and puddles a bit even though there are holes in my umbrella.

[slide: classical] I like to tell my general physics students that just about all their interactions with physical things in this world, with the exception of certain features of their computers, gaming systems and cell phones, are governed by the laws of classical physics. These are the laws discovered hundreds of years ago by Galileo, Newton and many other natural philosophers who were using the new empirically based scientific method. They used the knife of reductionism to pare down complex problems in order to ask simple questions of nature in the form of experiment and record results in the form of measurements. Despite the tinfoil-and-fudge equipment they were often forced to use (measuring time with a water clock? please!), theory advanced to account for ever greater levels of complexity. From these ongoing successes emerged the idea that this new enterprise was revealing an objective reality that was “out there,” independent of who happened to be looking. **[slide: classical, objective]** In other words, according to this realism if a tree burned in the forest and there was nobody there to smell it, it did indeed still produce smoke. (Or some other sensory variant on that theme.)

The signature element of classical theories is their determinism; that is, every event has a cause. **[slide: classical, predictable]** Once the initial conditions are known, one can simply grind the theoretical crank forward or backward to any desired time. In practice, of course, this sort of absolute knowledge is limited by our inability to measure with infinite precision, so some divergence between theory and experiment is to be expected despite replacing our water clocks with atomic ones. Nevertheless, due to the unrivaled success of classical mechanics, scientists of the 18th and 19th centuries believed we lived in a clockwork Universe. **[slide: classical, clockwork–>Lagrange points]** Here, for example, is a case of clockwork physics involving the law of gravitation. The yellow circle is the sun, the pale blue dot is the Earth or another planet and the green circles mark Lagrange points. Objects at Lagrange points experience gravitational forces that yield periods of revolution identical to the planet. If this were Jupiter, you would find clusters of asteroids at L4 and L5 named the Greek Camp and the Trojan Camp in honor of the *Iliad*. (Look! Liberal arts! Okay, I can do better...) On the other hand, you may find the L3 point particularly compelling because your evil twin lives on the "Shadow-Earth" located behind the sun where you can't see it.

Let's begin our tour of quantum theory, which deals with the microscopic rather than the macroscopic, with two statements from scientists who helped develop it. **[slide: quotes]** Richard Feynman said: "I think I can safely say that nobody understands quantum mechanics." And Niels Bohr said: "Anyone who is not shocked by quantum theory has not understood it." Look closely at your own field of study and you are certain to come across contradictory statements like these —I think they are an indicator of richness and interest. I think Feynman and Bohr are both warning us that quantum theory contains counterintuitive ideas that challenge the way we view the world through our built-in classical lens. The impact of these ideas on our conception of reality is still being explored in diverse fields such as religion, philosophy, and literature not to mention more closely related physical sciences. There are some who would argue that all human understanding takes place in terms of classical concepts fashioned from our direct experiences as macroscopic beings, so the impact of these quantum challenges can be minimized. According to novelist and scientist C.P. Snow, however, "No more profound intellectual debate has ever been conducted." Whether you agree with that sentiment or not, I hope that you will decide to participate in the debate and discussion in the spirit of open inquiry.

First, let's consider probability, the signature element of quantum theory. **[slide: probability]** Beginning in the 19th century with the discovery of radioactivity, processes that appeared random and unpredictable came to the forefront of scientists' awareness. The moment when a single nucleus will decay cannot be predicted and has no classical cause, only a probability of occurring during the next time interval. In the fully developed quantum theory, classical determinism is undermined even further. Consider the humble hydrogen atom consisting of a single positively charged proton and a single negatively charged electron in "orbit" about it. **[slide: probability, orbits]** Early models of the hydrogen atom were based on a solar system-like configuration because (surprise!) the mathematical description of the electrical force is the same as the one for the gravity force. However, this model was known to be inaccurate right from the start because even classical theory would require the orbiting electron to give off energy in the form of light and go into a "death spiral" ending with its collapse into the nucleus. **[slide: probability, spiral]** This is unsatisfying for a number of reasons, not the least of which is the fact that if stable hydrogen didn't exist then neither would heavier elements like carbon which is used to make vital bits of you and me.

Via a complex but very successful piece of quantum machinery called Schrödinger's equation, we now believe that the electron occupies "orbitals" that describe the probability of finding the electron at a particular location about the proton. **[slide: probability, orbitals]** Here brightness corresponds to probability, and you can visualize the fully three dimensional lobes and spheres by taking each picture and mentally spinning it about a vertical axis. The proton would be located at the center of each image. Consider the central image and note the black line that passes through it horizontally. This represents a zero probability of finding the electron anywhere on that line (which ought to be a horizontal plane in your 3D visualization, right? talk about flexibility of mind). Now think classically about this scenario: if the electron starts out in the top half of the atom, how does it ever get to the bottom half if it can't pass through the forbidden, zero probability zone? It turns out that the concept of a velocity which determines classical trajectories doesn't exist in quantum theory. You don't even get to ask the question "How does the electron go from top to bottom?" It is simply a fact that sometimes you measure the electron to be in the top half and sometimes in the bottom half.

In quantum theory the very act of measurement itself is fraught with deeper implications. Physicist Pascual Jordan put it this way: "Observations not only disturb what has to be measured, they produce it. In a measurement of position… the electron is forced to a decision. We compel it to assume a definite position; previously it was, in general, neither here nor there; it had not yet made its decision for a definite position. We ourselves produce the results of measurement." **[slide: probability, indeterminate states]** So in the language of quantum theory, a particle exists in an indeterminate state until we make our measurements, and the full, probability-weighted range of all possible outcomes is part of that state. Physicists David Bohm and Abner Shimony give us an evocative pair of phrases on this point: a quantum state is a set of potentialities and measurements actualize one of these potentialities.

Measurement is also at the heart of the famous Heisenberg Uncertainty Principle **[slide: HUP]** Heisenberg showed that for specific pairs of physical quantities we cannot know the exact values of both quantities simultaneously. The most widely discussed pair is position and momentum (classically, momentum is mass multiplied by velocity—think of it as the amount of oomph in a particular direction) and the uncertainty relation for them is written as **[slide: HUP,**

delta-x*delta-p] $\Delta x \Delta p \geq \hbar/2$. Now, it is a truism of publishing that every formula in a book written for the non-expert causes a loss of half the intended audience, but I know not one of you will go screaming off into the night because you have already absorbed the message “Don’t Panic.” **[slide: HUP, Don’t Panic]** Let’s consider this together: our lack of knowledge or uncertainty about position is called delta-x and our uncertainty about momentum is called delta-p. Note that their product is greater than something called aitch-bar, or Planck’s constant, divided by two. This is a tiny number **[slide: HUP, aitch-bar]** but not quite zero, so the greater than or equal to sign means, for example, that the better we know position the worse we know momentum because their product has to be bigger than this small number. Note that the uncertainty principle refers to something fundamental about nature—it does not speak to the issue of our *instrumental* limitations. We can improve our instruments, but we cannot improve nature. This is not good news for fans of determinism: the uncertainty principle clearly implies that complete knowledge of a system and therefore of its future is not possible.

In fact, if we know the position exactly so that delta-x is zero, the uncertainty principle implies delta-p blows up to infinity and we can’t know anything at all about momentum. Classically, this is nuts. It’s analogous to driving down the highway and having your GPS go on the fritz (or worse, your windshield blacking out) just because your speedometer is reporting an accurate value of 65 mph. Why don’t we notice these effects in our everyday, macroscopic lives? Because Planck’s constant is such a small number, **[slide: HUP, decimal form]** and we exist way up here in the ones place. To sense time increments at the granularity consistent with Planck’s constant you would have to be aware of a trillion trillion trillion divisions in each second. This is a rather tall order.

As you might imagine, not everybody was happy with the probabilistic nature of this new quantum theory. One such person was Albert Einstein who actually made a significant early contribution in 1905 by suggesting that light sometimes behaved like a particle, a discrete lump of energy called a photon. Throughout most of the 19th century it had been widely accepted that light exhibited wave-like character, not least because Maxwell's theory of light as an electromagnetic wave was incredibly successful and applications to radio communication had already begun. Now, physicists like their simple models and waves are meant to represent non-localized things with neither a beginning nor an end. Their behaviors include things like interference patterns and diffraction, the bending of waves that pass around obstacles or through openings. I sense you're itching for a demo, so let's observe the diffraction of light together. Put a couple fingers together like this and hold them close to your eye. Create a narrow opening between your fingers while looking at a moderately bright light source. Yes, it can be embarrassing because people will think you're a little weird, but if we all do it we'll all be weird together. What do you see? Alternating dark and light bands parallel to your fingers? That is a diffraction pattern and proof that light is a wave.

Particles, on the other hand, do not do these things but are discrete entities with well-defined trajectories. Not too long after Einstein hypothesized a particle-like nature for light, Louis deBroglie turned it right back around and suggested that particulate matter has a wave-like character, too. This has also been confirmed experimentally and finds use today in technologies like electron microscopes. Here again you see the significance of the observer in creating the reality of a quantum system: if you ask it a wave-like question you will get a wave-like answer, but if you ask it a particle-like question you will get a particle-like answer. According to quantum theory, all the stuff of the Universe has this dual nature. Particle and wave models complement one another, but matter and light are not "really" either one. And if you ever hear anyone use the term "wavicle," strike him smartly on the cheek and tell him it is inappropriate language. By the way, in case you are wondering, yes, you do have a wave-like nature that complements your already familiar particle-like nature. Unfortunately, you will never experience the joys of diffraction by passing through doorways or windows because the width of the opening required for bending your wave is trillions of times smaller than the diameter of a single atom.

Einstein's objections to quantum theory centered around its underlying indeterminate states (those sets of potentialities) and how they make the role of measurement an active process that selects one of the potentialities to create reality. According to his strongly held realism, measurement should be passive and reveal a *pre-existing* reality. Einstein therefore concluded that the inability of quantum theory to predict the outcome of a measurement was because it was incomplete and limited. After all, it refuses to answer questions a realist believes should have answers: How *does* the electron go from the top half to the bottom half? What will be its position *and* its momentum 1.83 seconds from now? His most famous objection is found in a letter to his friend and fellow scientist Max Born: "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one.' I, at any rate, am convinced that *He* does not throw dice." Similarly, Einstein's biographer Abraham Pais reports that during his interviews: "We often discussed his notions on objective reality. I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed the moon exists only when I look at it." (Aha! Now we're getting somewhere.) **[slide: title reprise]** No observer-created reality for Einstein, thank you very much.

In 1935 Einstein published a paper with two of his colleagues, Boris Podolsky and Nathan Rosen. Now known simply as the EPR paper, it purported to show through a thought experiment (a gedanken experiment) that quantum theory led to patently absurd results. The experiment involves pairs of so-called entangled particles, which is just a 50¢ word for particles that have interacted with each other. **[slide: entangled]** The quantum mechanical description of an entangled state has unique mathematical properties that make it more than simply "the sum of its parts." There is no classical analog to entanglement, and Erwin Schrödinger eventually came to the opinion that entanglement was "not *one* but *the* characteristic trait of quantum mechanics." The entangled state endures in its purest form as long as the two particles don't subsequently interact and entangle with other particles. This process of multiple entanglements that obscure each other's influence is called decoherence. **[slide: entangled, decoherence]**

Let's imagine creating a pair of entangled photons that travel in opposite directions. **[slide: entangled, photons]** We choose to create an entangled state such that one of the photons is horizontally polarized and the other one vertically, although it is not known ahead of time which one is which. (Polarization is a characteristic of light that can be measured—polaroid sunglasses block horizontally polarized light to reduce glare.) If you measure the one traveling to the left (call it A) **[slide: entangled, moving photons]** you will get horizontal polarization 50% of the time and vertical polarization 50% of the time in a random sequence for successively created pairs. Make particular note, however, that the polarization state of the photon traveling to the right (call it B) is known *without having to measure it* (you don't even need that analyzer at B) because it is always in the opposite polarization state of A. The states of A and B are correlated. **[slide: entangled, correlated]**

The EPR paper makes the further stipulation that the photons travel far enough before the polarization measurement occurs that during the act of measurement there is no chance for a light signal or other influence to travel from location A to B. This is know as the locality hypothesis—signals cannot travel faster than light in order to affect the other system. But look at the results of the experiment: the polarization state of B is known *at the very moment* the measurement is done on A. Thus, EPR is claiming that quantum theory calls for the properties at location B to be a direct result of a measurement at another location A so far away from B there is no possibility of A exerting an influence on B. This has become known as the EPR paradox. **[slide: EPR]** In another letter to Max Born, Einstein wrote: "I cannot seriously believe in the quantum theory because it cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance." **[slide: EPR, spooky]** In other words, although quantum theory claims its sets of potentialities are not definite until measured, Einstein thinks he has shown this requires some kind mysterious influence that travels faster than light, and no reasonable definition of reality could be expected to permit this. **[slide: EPR, hidden]** Therefore, in his view, quantum theory is incomplete and must be replaced by an improved theory that accounts for these so-called hidden variables that really ought to have definite values.

A stand off existed between what we might call orthodox quantum mechanics and the EPR hidden-variable theory for nearly three decades because there appeared to be no way to distinguish experimentally between them. This is not scientists' favorite state of affairs, but one could be agnostic on the EPR paradox without penalty (in this lifetime at least). **[slide: Bell]** But in 1964 an extraordinary theorem was published by John Bell, another of these physicists with a brain the size of a planet. Bell's theorem clearly shows that EPR-type hidden-variable theories cannot account for the same set of predictions made by orthodox quantum mechanics and that experimental situations can be created that distinguish between the two. Although Bell's theorem was largely ignored for a decade after its initial publication, it has since been recognized, improved and extended, and, yes, its predictions have been put to the experimental test many times over the past 25 years. The findings are incontrovertible and in favor of… orthodox quantum theory. EPR were wrong, there are no hidden-variables with definite values. Stuff at the microscopic level apparently does not possess discrete attributes that we are simply unaware of.

But wait, how then should we talk about the entangled pair of particles? If we can't have hidden-variable theories are we then back to spooky action-at-a-distance? Realism seems to have taken some pretty hard hits here. Are we *also* forced to chuck locality overboard, too, and conclude some faster than light influence? The consensus right now seems to be no. Our difficulty comes in thinking of the entangled pair as consisting of two things when it is actually a single entity no matter how far apart the original pair get. In his book *Quantum Reality* Nick Herbert, in an effort to free us from thinking of causal influences, describes these quantum influences as "unmediated, unmitigated and immediate." Well, that's okay in a descriptive sense, but in what I think is a more compelling image, Abner Shimony encourages us to consider the influence as "passion at a distance" rather than action at a distance to evoke, I think, the entwining of these two things into a new, special sort of relationship.

So… as my wife likes to say with distressing frequency, are you ready to talk about The Relationship? **[slide: relationship]** I'd like to engage in a little bit of what C.S. Lewis called magisterial poetry—using metaphoric and symbolic language—to make a few connections between our newly won quantum knowledge and our broader goals for learning, our aims of education.

Having served on the Honors Council for one year and two days I know for a fact (via measurement!) that Roberta and Julie serve the honors program very well indeed through their hard work and dedication. So I am afraid that the Honors Program is never in an unobserved state, and therefore the question in the title of this talk isn't answerable. I think there are always at least two people looking at the Honors Program, even at night in their dreams I dare say. So as all experienced scholars do when faced with such difficulties, I will define my way out of the problem. (This approach better not show up in any honors theses or my seat on the council is in serious trouble.) Let's do a thought experiment of our own and ask is the honors program there when nobody looks under the assumption that Julie and Roberta are in London and have forgotten all about it?

If the Honors Program were a microscopic particle, I am afraid we'd have to conclude that we couldn't say where it is or anything else definite about its state. But, of course, it's not an honors particle it's an honors program, and I think it's safe to say it's "there" with all of us who have interacted with it. We are entangled with the Honors Program. It happens in seminars, in discussions, in culture connection, in conversations, while doing research for theses and papers, the list goes on. And while in a strict quantum mechanical sense these multiple interactions over long periods of time ought to result in decoherence, from a learning standpoint they lead to strong interconnections and deeper understanding. Our potentialities become more abundant and more subtle, so we can respond to questions with more than horizontal-vertical or yes-no answers. Questions are the world's way of measuring us—when we answer we actualize one of our potentialities and put it out there as our reality. In doing so, we have to drop out of our entangled state, but only for a moment because we know the world is changing and there is always more to learn. As we re-entangle, we'll leave our answer behind with a provisional status tag attached to remind ourselves and others that we're still thinking about it. Because we understand deep down that no matter how certain it seems today, tomorrow brings a non-vanishing probability of change.

So if your self-image has room for another pixel (perhaps between the particle pixel and the wave pixel) I encourage you to think of yourself as a single, entangled entity with the Honors Program. Create a new passionate relationship via as many interactions as you can fit in your time here. Accumulate great rafts of potentialities. **[slide: relationship, hooray]** Then take the Honors Program with you into space and time on your journey of lifelong learning.

[slide: bibliography]

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