Interview with Prof. David Wineland for *Frontiers for Young Minds* on April 18th 2021

How To Catch An Atom: Tales on Time-Telling and Future Applications

Noa Segev: Ok, so the first question is: what attracted you to the field of ion trapping?

Prof. Wineland: Well, it is a bit of a long story—but as a kid, I was always interested in mathematics. Then when I got to high school, I took my first physics class and I liked the way relatively simple mathematics could explain a lot of things we see around us. So, following this, I got my college degree at the University of California Berkley, and then I went to graduate school at Harvard starting in 1965. Actually, when I started at Harvard, I thought I was going to be a particle theorist, but I figured out that you should be really smart to do that. Anyway, I always liked to do things with my hands, and so I looked around at experimental laboratories and joined an atomic physics lab. My thesis advisor was Norman Ramsey; he was a famous atomic physicist from the 20th century. At the time I joined his group, his focus was on masers. Masers are like lasers; the "m" stands for microwave, but the principle is just the same as the way lasers work. He and his colleague Daniel Kleppner invented and demonstrated the hydrogen maser, which had the application of making a very good clock. Anyway, during the time I was in graduate school, I was looking ahead towards my future and I was reading about things other people were doing. I became interested in the work of Hans Dehmelt at the University of Washington. He was doing high-resolution spectroscopy on trapped atomic ions and that attracted me because they can also make very accurate clocks. Anyway, that's what attracted me to the ions and the trapping, so I got my feet wet in Hans Dehmelt's lab. In 1975 when I went to NIST, the National Institute of Standards and Technology, I was in the Time and Frequency Division where their main business is to make atomic clocks and things like that, where ions could play a role. Anyway, that's how I got into the field of ion traps.

Noa Segev: What initially drew you to high-resolution spectroscopy, specifically?

Prof. Wineland: I think it is just the whole thing about precision measurements. As in the case of clocks, you are trying to make them very accurate and you have to account for a lot of things that perturb their measured frequency. I like the detective work aspect of it; figuring out how to account for all these environmental effects. You have to carefully characterize the effects to improve the precision of the measurements—I like that aspect of these very precise measurements.

Noa Segev: Yeah, I understand. Ok, so I think the answer is "yes", but I will ask anyway. Was the aim of controllably manipulating single particles on your mind from the beginning of your work? And if so, was it oriented more towards theory or application?

Prof. Wineland: Well, to answer the second part of your question—it is really oriented more to applications. In all the things I have been involved with we do some theory, but it is more to back up experiments, so my interest has always been in the experimental part of the work. But as I said, we need theory to back up and help explain what we are trying to do. And what was the first part of your question?

Noa Segev: Was the aim of controllably manipulating single particles on your mind from the beginning of your work?

Prof. Wineland: No, for the clock business, we typically worked with large number of atoms, or ions, in our case. The reason for doing that is just that you can get stronger output signals. We talk about signal-to-noise ratio, and typically it turns out that the signal-to-noise ratio is proportional to the square root of the number of atoms or ions, which is the reason to use large numbers. But it turns out that the interest in going to single ions was just that we could control the environmental effects much better than we could with an ensemble of ions. One example is that the measurements are precise enough that we have to worry about the effects of the motion of the ions or atoms.

Noa Segev: Yeah, you mean the time dilation and other effects?

Prof. Wineland: That's right, exactly, and it's just that we could do a much better job of controlling the motion if we went to single ions. That was one of the big motivations.

Noa Segev: Was it a clear direction that the field was heading, or did you kind of lead it?

Prof. Wineland: I think it was just a path that anybody else would have thought of eventually. My adviser at the University of Washington, Hans Dehmelt, his claim to fame was a precise measurement of the magnetic moment of the electron, the strength of the magnet associated with the electron. I don't know if you saw in the news last week or so, there was a big splash about measuring the magnetic moment of the muon, because the precise measurement could potentially reveal some new physics when compared to theoretical value. Anyway, for the electron magnetic moment, the theory is very difficult but is basically governed by quantum electro-dynamics, which was pretty well understood. The measurement precisions are so high that you could make very precise tests of the theory. For the electron magnetic moment, the experiment and theory now agree to about 1 part in 1012, which is one of the strongest tests of quantum electrodynamics theory. When I was at the University Washington, experiments were first being done on ensembles of trapped electrons, but it became clear that we could do measurements more accurately if we used just one electron. So perhaps my most notable project there was to isolate single electrons and do some simple manipulations of them. These manipulations were very similar to how we now deal with single ions, for example.

Noa Segev: Ok. So, the whole issue of control and isolation as a necessary requirement for studying quantum systems—was it clear how to implement it into practical applications?

Prof. Wineland: For atomic clocks, the direction was straightforward. The main thing was to make better clocks. But, as you know, in 1995 there was a big wave of interest in quantum computing that started. The initial application that got people interested, in particular government agencies, was that a theorist, Peter Shor, in 1994 came up with an algorithm that showed if you can build a quantum computer, you could efficiently factorize large numbers. The reason that's interesting is that basically many encryption methods, such as RSA, derive their security from the inability to efficiently factorize large numbers. So, a quantum computer would have a big impact there. And I would say that application really fueled the initial interest of government agencies in quantum computing. But in corresponding with Peter Shor in the last year or so, he has said that classical cryptographers have come up with new algorithms where, as far as he knows, a quantum computer can't crack the codes. So that application of quantum computation might not have impact in the future. But what has happened in the meantime is that many physicists think that the important application of quantum computing ideas is to be able to simulate other quantum systems. One potential application that is simple to state is that maybe if we could make a really good quantum computer we could, for example, simulate the action of molecules that might be used in drug therapy, or something like that. We could actually simulate their behavior without actually having to synthesize them in the lab and test them out, which would be of great value. So, this idea of simulation is potentially one of the key applications. Another example comes from Richard Feynman, a great particle physicist—he was credited with the early ideas of making one quantum system simulate another. He was interested in, for example, simulating the dynamics of nucleons and other elementary particles. And this is still on the table; that's the kind of thing we hope to be able to do. And, as you know, as a group we are kind of just scratching the surface right now of what might be done, but we are optimistic that this will eventually happen.

Noa Segev: Yeah, that's interesting. Ok, now more specifically about your contribution. I saw that you had a very wide and vast contribution to the fields of ion trapping, laser cooling, and single-particle manipulations. But for the paper it would be nice if you can, and if not that's ok, if you could highlight what you consider as your main contribution in each of these areas?

Prof. Wineland: Well, I think you know that the basic principles of ion trapping were out there before I came along and, in fact, Hans Dehmelt shared the 1989 Nobel Prize in Physics for being one of the inventors and developers of ion traps. So, the basic techniques of ion trapping were there. Personally, one of the most gratifying things for me was the idea of laser cooling. I had this idea, and actually a couple of other people independently had the idea—but you know, to be able to have this idea was a big thrill. And then, when I was at NIST, to be one of the first to demonstrate it in our lab—that was a big thrill also. And later at NIST, we extended the simple ideas of laser cooling, and what we can now do is cool a bound particle to the ground state of its motion, which is the limit of cooling. We don't need to do that to get what we want for clock accuracy, but for the ideas of quantum computing we do want to realize ground-state cooling as closely as possible. That is, we do want to start the ions our in their ground state of motion, and that was a key part of what enabled us to do simple demonstrations of quantum computing logic gates. Personally, probably the biggest highlight was doing the first laser cooling experiments, because when I was a post-doc at the University of Washington, I was assigned to the task of just working on electrons. So, when I went to NIST after my post-doc, it was the first time I had control of what I did, so that was the first experiment that I did with other colleagues at NIST. And that was personally a big thrill, to be me on my own so to speak.

Noa Segev: Yeah. And what sparked this idea for you? The laser cooling?

Prof. Wineland: It's actually one thing I tell grad students. I think at the grad student or post-doc level, one shouldn't get too locked into their assigned tasks; they should do some reading of material outside of their particular project. For me, I was just doing some reading that wasn't directly related to what I was doing as a postdoc. Lasers had been around for twenty years. The big step for atomic physics was that people came up with lasers that you could tune, so that you could manipulate or drive multiple transitions on a number of different atoms and ions. One of the papers I read was written by Arthur Ashkin, who later shared the 2018 Nobel Prize in Physics for his work on applying forces to atoms and more macroscopic particles. I was reading some of his early papers on the rather large radiation pressure forces that could be applied to atoms. From reading a few of these papers, you just need to know about the doppler shift, and that the atoms absorb radiation at particular frequencies—then, out of that falls this idea of laser cooling. It is really pretty simple, and I will take just half a minute here to try and explain. The idea works for an atom or ion that isn't trapped but, for simplicity, let's say they are trapped. When the atom moves against the direction of a laser beam, the frequency of the laser beam as observed by the atom is shifted to a higher frequency by the Doppler effect. So, if you tune the laser slightly below the frequency where the atom wants to resonantly absorb the photons, when the atom is moving towards the laser source, it upshifts the frequency of the laser source; and then it will absorb and reemit or scatter at a high rate. And when it scatters that's what gives this radiation pressure. On the other hand, when it moves away from the laser, the Doppler shift is in the other direction, so it shifts it out of resonance. So, when the atom is moving towards the laser, it experiences the radiation pressure which acts to slow it down; and when it moves away, the scattering tends to speed it up. But since it is shifted farther away from resonance, the scattering is smaller. So, what wins out is the cooling force that tends to slow it down when it is moving against the laser. And that's the simple idea, and it is pretty straightforward to work out what the limits to the cooling are. Anyway, so that was kind of a thrill for me to kind of work this out, and when I went to NIST, we were able to do it rather quickly after receiving the support. And, as you mentioned, the reason it's important for clocks is to suppress Einstein's time dilation shift.

Noa Segev: Yeah. And the radiation pressure is equivalent to the momentum of photons, or is it different?

Prof. Wineland: No, it's the same thing. When an atom absorbs a photon, it will get the momentum kick against its motion from the photon. And when the atom emits the photon, it may not emit isotropically, but it will emit symmetrically—and so, on average then, when it emits a photon there is no net momentum kick—it averages out either forwards or backwards. So, the idea is that, when it absorbs, it gets this force against it—the momentum kick against it—and that's the radiation pressure effect.

Noa Segev: Ok. About ion trapping—would you say there is anything additional to say rather than explain something general about how electromagnetic fields confine...?

Prof. Wineland: The way the traps work in three dimensions is a bit subtle but, in one dimension, we can make a simple electrode structure and, by applying different electric potentials to the electrodes, we generate electric fields that provide a harmonic well for charged particles. A good analogy for two dimensions is to think of a marble in a bowl. If the marble's kinetic energy is gradually reduced, its amplitude is also reduced. It's a bit more subtle how we do it in three dimensions but, in effect, it's like extrapolating the two-dimensional well to three dimensions.

Noa Segev: Ok. And do you think it is possible to explain it with simple kind of repulsion and attraction balance that somehow confines...or would you just leave it with the analogy?

Prof. Wineland: The simplest picture I think I can come up with is: with this electrode structure that is chosen in a particular way, we can make the electric fields act just like this bowl. And the idea is that, in the center of the trap, if the atom moves one way it will experience some electric field that pushes it back towards the center. And similarly, when it moves the other direction, it will also experience an electric force that pushes it back towards the center.

Noa Segev: Great. Ok, now a few questions about atomic clocks, which I am not precisely sure about. So first, I understand there are two parameters of the frequency itself you work with, related to the specific energy of the transition, and the width (or hopefully the narrow width) of the frequency around the resonance. Are there additional parameters which are taken into account?

Prof. Wineland: No, I would say those are the two key things. We want to choose a transition that absorbs photons over a very narrow range of frequencies; when this absorption signal is maximized, it tells us that the laser frequency is tuned to the atomic resonance. If the absorption is not maximized, we need to change the laser frequency to again maximize the signal. We want to choose this absorption feature as narrow as possible, to make the laser frequency as close as possible to the absorption frequency. Finally, we want to choose a transition with an absorption frequency as high as possible; this is because when we count cycles of the laser oscillation, we can more finely define a specified time interval, such as the second.

Noa Segev: And the reason that you, as I understand, always choose a transition from the ground state to an excited state, and not between two excited states, is because of the lifetime of the state, or something else?

Prof. Wineland: Yeah, that's basically it. The initial state may not be exactly the ground state, but we want it to be very stable and long-lived compared to the upper state. And of course, if the atoms absorb radiation they can decay as well, so that's why we choose a very narrow absorption, because a narrow absorption is equivalent to saying that the atom has a long lifetime in the upper state.

Noa Segev: Ok, and the last thing which might be too technical but I myself didn't exactly understand. I think it was your mercury paper about the transition from S to D. I am not exactly sure what's your detection if the transition was made—was it another radiation from another state?

Prof. Wineland: Yeah, so in the simplest version of the mercury experiment, we had one transition that had at a very narrow absorption width; that was the ground S state to upper D state that had a line with a few Hertz. This was the clock transition. But there was also another transition from the ground S state to the P state, which had a very short lifetime of around two nanoseconds, and so it did two things for us. One is that we could use that transition to do the laser cooling; and two, we could also use it to detect the absorption of the clock radiation. The idea there was to think about the three levels: the upper P level and the upper D level, and then the ground S state. So, the clock was based on the S-to-D transition. But because the P level had a very short lifetime, we could use that transition as to do the laser cooling. But also because the P level decays so rapidly, we could use the scattered light from the S-to-P transition to tell if the ion was in the S state, or if it was up in the D state, scattering on the S-to-P transition would not occur. With this method, we could tell if the ion was in the S state, where it would scatter about a 100 million photons per second. When it was in the D state, it wouldn't scatter at all. So, just by capturing a small fraction of the scattered light, we could tell with essentially 100% efficiency whether the ion was in the S or the D state and, in a simple way, tell if the ion made the transition from the S to D state.

Noa Segev: Ok, and since the initial state was that all the ions were in the ground state, you weren't worried about any additional excited states, or anything else that could…?

Prof. Wineland: No, at least in the simple example of mercury, those are the three states that came into play. And there are a lot of similar neutral atoms and ions that can be made into to a three-level kind of system. This basic idea of detection is fairly ubiquitous in atomic physics, where we have one transition you can scatter lots of light from and tell if the other transition is made.

Noa Segev: Yeah, ok great. Now we will move on to the more personal part, I think you already answered it about what is your discovery/achievement/contribution that is most valuable in your career. So, I think it is the laser cooling which you mentioned, right?

Prof. Wineland: Yeah, so I was working with a group of people, but personally, that was the most exciting thing for me. As I said, I independently had the idea and then, at NIST, we were able to do one of the very first demonstrations. That, coupled with the fact that it was the first time I could be self-directed, made it pretty exciting. With my colleagues, we have accomplished other important steps over the years as well, but that was personally the most satisfying one for me.

Noa Segev: Any other specific achievement that you would like to mention?

Prof. Wineland: At NIST, a long-term goal has been to make better clocks. One of my close colleagues there, Jim Berquist, was leading the project to make an atomic clock based on an optical transition in mercury. We were working together but he was the leader and the laser expert, and it was a long but enjoyable journey. I think one of the things we were proud of is that we started on this experiment in the late 80s and after many years of improvement, by around 2005, this clock based on the S-to-D optical transition in mercury was more accurate than the cesium clock which, up until that time, was the best clock. An interesting part about that was that the duration of 9,192,631,770 oscillations of the "hyperfine" transition in cesium-133 was adopted in the mid-1960s, as the internationally agreed on definition of the second. Because of that, a lot of work was directed towards improving the cesium clock but, in 2005 with the demonstration of the mercury ion clock, it was the first time that a clock was better than the current cesium. The definition of the second is still currently based on the hyperfine transition in cesium. But because optical clocks are substantially more accurate than cesium clocks, people are looking towards maybe changing the definition of which atom or ion will be the basis for the definition of the second. One problem that exists is that, currently, there are several neutral atoms and ions which are better than the current cesium clocks, but there is no clear winner. If we chose a new atom or ion to be the standard, two years down the road there may be another one which is actually better. I think we are always going to be in this situation. So, being scientists in a lab, we don't really care about what the definition of the second is based on—we just want to make better clocks and be able to compare them

Noa Segev: A question about the future: what do you find most exciting about the future of single-particle physics?

Prof. Wineland: Well, maybe not single-particle physics, but with the precision we have with these new ion and neutral atom clocks, we might be able to test a number of theories for how the transition frequencies might be affected by exotic physics such as dark matter, for example. In addition, if we can use our quantum bits to make a powerful quantum computer, simulation of other quantum systems is potentially the biggest area of future application. Of course, atomic ions and neutral atoms are only one kind of qubit that might be used to make a quantum computer. A lot of people are working on superconducting qubits, and there's other physical systems that might eventually turn out to be better. But at this point, there is no clear winner—which is why these different potential platforms for making a quantum computer or quantum simulator are all interesting.

Noa Segev: And how far off do you think we are from quantum computers?

Prof. Wineland: I don't know; it's hard to say when we might be able to make what is called a universal quantum computer. First, we want to get better control of our qubits and quantum operations than we have right now. In addition, there's an entire sub-field of quantum computing that is directed towards correcting for errors, and we can only do relatively simple demonstrations of that now. And these are just some of the ingredients that are needed to be able to have a fully useful device. So, the next quantum computers will be able to solve relatively simple, useful problems, and hopefully, as the entire field progresses, we're going to be able to do more complicated things that will have important applications to society in general. So, I'd say there is no exact point in time we can say "we made a quantum computer", because we make baby ones now and they will undoubtedly get better and better. And we may be getting closer to doing useful simulations, such as one that tells us something new about physics that we didn't know before, or simulates the dynamics of molecules that might used in drug therapy without having to synthesize them in the lab. If we can really do something like that, that will really set things on fire. I could believe that might happen in the next 10 years. Maybe not, but I think we're getting there.

Noa Segev: Ok. What do you think about Feynman's famous quote: "If you think you understand quantum mechanics, you don't understand quantum mechanics"?

Prof. Wineland: Well, he was obviously a smart guy, but I think he was being a bit flippant by saying that. There are some unusual things that happen in our quantum world. One good example is Einstein-Podolsky-Rosen or EPR experiments, do you know what I mean by that?

Noa Segev: Yes.

Prof. Wineland: You know Einstein was bothered by the fact that quantum mechanics would predict this "spooky action at a distance"...

Noa Segev: Which is non-locality, right?

Prof. Wineland: Yes. And so, I think that this apparent non-locality, this "spooky action at a distance" is real, and probably the experiments that most conclusively demonstrate this are based on photon-like EPR experiments. So, I'm guessing that's in part what Feynman was alluding to. This "spooky action at a distance" seems really strange because we know that we can't communicate information faster than the speed of light. But there is this effect, that something appears to happen faster than the speed of light, this apparent super-luminal communication you might say, and I am guessing that this was in part what Feynman was alluding to… It is worth noting that the 2022 Nobel Prize in Physics was given to three scientists who pioneered the experimental study and demonstration of these effects.

Noa Segev: But would you feel that it is beyond our capacity to understand, or is it just…?

Prof. Wineland: No. maybe I am just too pragmatic, but I think this apparent action at a distance is real, it's just one thing we incorporate into our thinking, and it becomes pretty natural to think that way. It does seem a bit strange, but it's there.

Noa Segev: Ok. If you weren't a physicist, what would your profession be?

Prof. Wineland: Well, I don't know. It would probably be something technical. When I was younger, I liked cars and motorcycles, and my dream career was to be a racing car driver or motorcycle racer or something like that. But I don't know… When I was very young, I always liked airplanes and I built and flew model airplanes. So, I thought I would become an aeronautical engineer just because I liked airplanes. Probably I would have done something technical like that if I hadn't become a physicist. So, yeah.

Noa Segev: Ok. This question you alluded to earlier, but what is most important for you to pass on to your students as their advisor? So, you mentioned being independent and reading things…

Prof. Wineland: Yes, what I'm thinking of is that, if they go to graduate school, they will be assigned to (or they will latch on to) some particular project. So, what I was referring to is that I think it's always useful to not just focus in on the exact topic that you are working on, but to branch out a little bit and do some reading that's not obviously related. In my example with laser cooling, I knew basically how photons and atoms work, but in doing some outside reading, some of these papers were pointing out how strong these forces—these radiation pressure forces—could be. That got me to incorporating the Doppler shift, which naturally led to cooling. But the more general thing I would say to students is that, first of all, you don't want to go into any field to win awards. It's obviously wonderful to receive a Nobel Prize but generally I think that if that's your focus, it's usually a path towards disaster. A couple of colleagues that I knew reasonably well were kind of obsessed with winning the Nobel Prize, and it just destroyed them because, when it didn't happen, they felt like failures. So, my main advice to students is just that you want to find something you like, and if you like it, you are going to work hard and spend a lot of time on it, and I think you will be successful. And even if you change your mind about what you like, what's interesting to you, I think that's ok. There's obviously shortcomings to that—you maybe don't want to go through graduate school as a physicist and then try to become a doctor—but in general, I think you want to keep your eyes open to changes. Similarly, if you are choosing a direction just to make money, you are likely not going to be successful or you'll not enjoy what you've chosen. So, I think that's very important. And, as I said, I think with reasonable limits, it's fine to change—up through college you can always change. In fact, my roommate that I had in my first year in graduate school was actually a concert pianist; he'd gone to Julliard, very accomplished guy, and he gave performances when I was in graduate school. But he just decided he wanted to become a physicist, and he was actually very good [laughs]. So, you don't have to decide when you start college what you going to do, you want to look around and you can change.

Noa Segev: Ok, and if you mentioned, I actually wanted to ask you about the meaning of the Nobel Prize for you: is it just a general recognition of the field? Or…

Prof. Wineland: Well, I think the first thing to say is that it was a wonderful experience for me to have received the Prize, but two additional things should also be said. First, a lot of other very well-qualified people might have received it instead of me. Another thing to say, particularly in my line of work, is that, except for graduate school where I was working basically alone on my own project, I was always working with other people as kind of a team. That was certainly the case when I got to NIST. Although I was the group leader, we basically ran things together, kind of like a committee; I certainly wasn't the ruler on high, giving orders; rather, as a group, we discussed what would be the best things to do. Certainly all the experiments I worked on at NIST were done working with other people, so being able to work in groups was certainly important for the work that I did. So anyway, to answer your question, I think me receiving the Prize is more a reflection of all the things that were accomplished in these group settings. Maybe I started some of the ideas and things like that, but certainly it wouldn't have happened if I was working by myself. So, as I said, I think there are a lot of very deserving people in any year. I am actually not informed on the details of the process but, from my experience, basically the Nobel Committee solicits nominations and those may lead to a certain topic that's interesting and chosen for that year. The Committee certainly tries to do a very thorough job by soliciting outside opinions on the nominations; they don't want to make mistakes [laughs]. But anyway, just to summarize my answer to your question I think although it was wonderful to have this happen, the award could have gone to a lot of other people that are doing good work, and for some reason they will not receive it. Also, I don't want to overstate this, but physics is a bit faddish—certain topics will be popular at certain times, and there will be other topics that come along that are also popular and intriguing and will receive attention. There's a lot of interesting stuff going on, and some things will bring more attention than others at a given time. Certainly, there is an element of luck I would say, being in the right place at the right time.

Noa Segev: Yeah, that's something that pretty much all Nobel Laureates mentioned. Ok, the last question is, well not so much a question, just if there is anything else that you would like to share from an educational point of view to children, whether it's on how to live a happy life, successful life, how to choose a profession, whatever feels right for you to share.

Prof. Wineland: I think I will be restating myself a little bit, but I think that students want to find something to pursue that they are truly interested in. I've always felt that the work that I do is more like a hobby—that I would probably be interested in this kind of thing even if I wasn't a physicist. Of course, one needs to be practical—I mean the students have to think about getting a job that will support them—but I think other than that, there's a lot of choices for what they might do. And there is no question that, for almost everybody, there's going to be hard work involved; but if you enjoy what you do, that will be the real reward.

Noa Segev: Yeah, but the actual fact that it's so reproducible, the answer, means a lot because still people today have many considerations, and not many put their interest in such a high place, so it's useful.

Prof. Wineland: Yeah.

Noa Segev: Ok, so many, many thanks and as I said we will send you the paper for editing and remarks before we publish it. And I really enjoyed it, so thanks a lot.

Prof. Wineland: Thanks, I did too.