Hello, I'm Hank Green! Welcome to Crash Course Chemistry. Last time we left off with Mendeleev believing he had discovered a cosmic, mystic reality about the world, but in fact he had discovered the effects of his worst enemy: tiny invisible particles. Electrons, which are so marvelous and peculiar that it wasn't until eighty years after Mendeleev's first periodic table that they were really understood by anyone and to this day still very, very few people understand them. But in like ten minutes from now, if all goes according to plan, you will be one of those people. So let's do this.

[Intro Music]

(00:43)

=====Snobby Scientists=====

In 1865, before Mendeleev published his first periodic table, a young chemist, and activist, John Newlands published a paper on the periodicity of elements, comparing their repetion, at least the first two rows of it, to a musical scale. All do re me fa sol la ti do and stuff. Maybe, he theorized, lithium was just sodium but an octave higher. Maybe they were, in a sense, the same note. He delivered this idea to the Royal Academy, the most prestigious group of scientists in the world and they basically laughed him off the stage.

[Words scroll down screen]

"Music is art and chemistry is science. Now describing science in an artistic way might be a fine parlor trick for helping little babies or women understand the work you do but they have no place in the Royal Academy." That's my impression.

But there was no way of course of knowing that it turns out John Newlands, when it came to the actual, functional, physical reality behind the periodicity of elements was more right than any of the scientists who laughed him off the stage that day.

And he never got to find out how right he was. We didn't discover that his analogies were barely analogies until long after his death but it turns out that reality is like a kind of music, and maybe you want to laugh me off the stage right now but bear with me.

(01:57)

=====Great Dane/Bohr Model=====
Before quantum mechanics, scientists envisioned the atomic world as just a miniature macroscopic world. Electrons seemed to just be particles orbiting around a nucleus. In fact, there was a great Dane [Great Dane dog appears on screen] ...no Nick... other kind of Dane... Niels Bohr, yes. Like certain other people I might name, he sometimes felt like he was in the shadow of his older, more successful brother, an Olympic soccer player, while Niels' handwriting was so poor that he had to dictate his PhD thesis to his mom. Nevertheless, he was an ingenious physicist. You might remember a couple of episodes back, when John Dalton determined that elements only exist in discrete packets of matter. Well by Bohr's time the same thing was known for the energy given off by electrons. That energy only came off in what ended up being called "quanta" which is the root of the term "quantum mechanics." In 1913, Niels Bohr came up with a simple model for describing these energy levels for a single electron in hydrogen merely assuming circular orbits. So there is some truth to the framework of thinking of electrons as particles. However, when he or anyone else tried to apply this to more complicated atoms, they failed miserably. Long story short, electrons don't really behave like particles; they're better described as waves. So we've known for fifty years that this is a an entirely inaccurate way of visualizing an atom. Nuclei, yeah, you can think of them as solid particles but not electrons. Electrons are wave-particle dualities. I think of them like resonance in the universe, and just like a single string producing multiple notes on a guitar, an electron can exist in a number of different harmonics. This isn't an analogy either, quantum physicists actually talk about the harmonics of electrons. After a few years of trying to figure this stuff out, a couple of very smart physicists started to look at electrons as waves, standing waves. This makes a lot of sense, even to us lay guys. When you swing a telephone chord in a straight line there are a discrete numbers of nodes, depending on the tension and the frequency, or in better physics terms, "energy" you put into the system. The same thing happens to an electron around a nucleus; a standing wave is produced only at certain energy levels. Anything in between is not allowed. An Austrian physicist, Erwin Schrodinger, who you may have heard of because of his cat, is the first guy who developed a mathematical model where the electron was assumed to be a standing wave.

(04:13)

=====Electrons as Music=====

Now, it is time to move a little bit into the realm of metaphor here because I'm gonna tell you how I think, how I think of electron shells and orbitals, not really how they are. The music of electrons is not simple music. It's no three chord song; it's like Beethoven but with more rules, hard fast rules that can't be broken. In that way, at least, it's more like science than art.

(04:44)

=====Electron Shells and Orbitals=====

Electrons exist in orbitals a bit like the individual notes on a keyboard. But the orbitals tone isn't complete until it has two electrons in it, and orbitals exist in shells. The first shell just has a single orbital, an s-orbital, which can only fit two electrons. That's why the row of our periodic table only has two elements. They play simple song those two and a song that every other element will build upon. The second electron shell is physically larger and thus can include more than just the s-orbital. A second sort of orbital with three different configurations is added, the p-orbital. Instead of just being a single tone the p-orbital is more like a three part harmony with two electrons in each part for a total of six. Those six electrons of the p-orbital plus the two s-electrons are the eight electrons referred to in the octet rule: the desire for most of the lighter elements to have eight electrons in their outer shell, just like a musical scale. This is often described in terms of fullness or satiation, as if the atoms are devouring electrons, but I prefer to think of an incomplete electron configuration as a cacophonous symphony playing in different keys and at different tempos. The closer you are to harmony the worse it is until one final note chimes in, that eighth note and everything crisps into full resolution, a deep, complex tone emerges and the atom settles into complete harmony, the harmony of the noble gases. That's just how I think of it.

(05:54)

=====Electron Configurations=====

And just like with music, there's a bit of notation to learn as well. It's important to know how to write out what we call "electron configurations," a condensed way of showing exactly where all of an atoms electrons are. First, we write the number of the shell, then the letter of the orbital, then the number of electrons in that orbital, and repeat until we run out of electrons. So for hydrogen, with just one electron it's $1s^1$. For fluorine it's $1s^2 2s^2 2p^5$.
Now as we move to the third row, an interesting thing happens; the third shell adds a third kind of orbital: the five part harmony, with ten electrons, of the d-orbital. But you might be saying, "There's still

only eight elements in the third row. What's up with that, Hank? It's all lies, I'm leaving!" Okay calm down, the atomic symphony composes itself in peculiar ways. Because building the 3d orbital requires a lot of energy, electrons actually go into the s-orbital of the fourth shell, 4s, before going into the third shell's d-orbital. This is actually a trend that continues and to remember it just write out the following on a piece of paper--these are the orbitals we know and all the shells that we've seen exist. To figure out what order to fill them in, you just draw a diagonal line from the top right to the bottom left as you go. So 1s first, then 2s, then 2p 3s, then 3p 4s, 3d 4p 5s, 4d 5p 6s, and so on. Armed with this knowledge you could write out the electron configuration for pretty much any element on the table. Iron, number twenty-six, would be $1s^2$ $2s^2$ $2p^6$ $3p^6$ $4s^2$ $3d^6$. Now there are a couple of elements that have weird electron shells, but you can just look it up on Google.
An interesting thing about d-orbitals, and the even bigger, more electron rich f-orbitals, is they don't really need to be filled quite as much as the s and p's, because they're literally shielded beneath the s-orbitals of the next shell. The s and p-orbitals I think of kinda like the trumpets and violins: it's really terrible when they sound bad, but the base notes, deep and rich, hide a bit underneath the rest of the orchestra, just like the d-orbitals literally hide underneath the s-orbitals that have already filled above them. Yes these incomplete orbitals affect them, but because their shielded, these middle of the chart elements are generally less reactive and happier to bump electrons along from atom to atom making them conductive, or just hanging out together in big masses of electron-sharing lumps of metal.

(08:17)

=====Ionization and Electron Affinities=====

So why are orbitals useful when it comes to understanding how an atom is likely to react? Well first, it really matters how much energy is required to remove an electron from an atom to form a positively charged ion. This energy is called "ionization energy." If there are several electrons being removed this is a step-wise process, starting with the electron at the highest energy level, the outermost one. Since the outermost electron has the highest energy, there's the least energy necessary to remove it. More energy is needed to remove the second furthest one out and so on. And of course when all the electrons in the outermost shell are removed there's a really large energy jump necessary to remove an electron from the next shell down because that shell will be isoelectrically analogous to a noble gas. Just like how atoms are isotopically the same when they have the same number of protons and neutrons, atoms are isoelectrically the same when they have the same number of electrons. And just like there's energy associated with removing an electron to form cations, or positively charged ions, there's energy associated with adding electrons, usually to fill an orbital to achieve a stable two or eight electron shell configuration. Just like with the ionization energy there's a discrete energy jump involved with the adding of an electron. That energy is called "electron affinity."

(09:28)

=====Periodic Table=====

Now, you ready for the real mind melter? If you're following along in your periodic table, which of course you aren't, you may have noticed a little something interesting. On the left-hand side you have your s-orbitals--one, two, three, four, five, six, seven s. In the middle, you got your d's: 3d, 4d, 5d, 6d. And on the top right, 2p, 3p, 4p, 5p, 6p. And below of course, in the little island of the lanthanides and actinides, your f-orbitals: 4f and 5f. And so, with just a glance at your periodic table you can work out electron configurations and elemental stability and the fundamental, physical reality of the elements. That's why this thing is so beautiful to me, because when you get to know it, you see all those flawed, competing harmonies and the actions and reactions that occur because of them, changing their song into something more stable and powerful and eternal together, making everything.

(10:18)

=====Big Picture=====

Now as I've gone through today's episode I've described electrons mostly in musical terms as vibrating waves, harmonies in the fabric of the universe and that's, indeed, how I like to think about them, but of course, that isn't a complete story. And I have gotten sick of people telling me that the human brain is incapable of imagining the reality of the subatomic. So I'm actually just going to serve a big heaping pile of reality on you right now no matter how odd it turns out to be.

There are, a number of everywhere-permeating fields in our universe. One of those, is the electron field. In order for an electron to exist, there has to be an excitation of the electron field and we can describe those excitations as waves, just as a wave in the ocean is an excitation of the water. At any given moment, the electron can be anywhere within the function of the wave. But waves are defined not by harsh boundaries, instead they're strong in some areas and weak in others. The strength of the wave at one certain point in space determines how likely it is that you will find an electron there at any given time if you measure. And so if we're trying to understand reality we should not think of electrons as circling around the nucleus of an atom like planets around a star, but instead as an excitation around the nucleus and the shape of that excitation is the orbital. Orbitals are precisely the reason that everything exists. They are the root and the key and the nexus and the crux and the keystone and every other metaphor of not just chemistry but existence.

=====Summary=====

Thank you for watching this episode of Crash Course Chemistry. I hope it blew your mind. If you were paying attention you now know about a poor young man who was laughed out of a meeting of snotty scientists because of being far more correct then anyone could ever have imagined. About a great Dane whose incorrect model of the atom was pretty amazing anyway. About electrons as music, and electron shells and the orbitals they contain. How to write out electron configurations, what ionization energies and electron affinities are, and how the periodic table ties all of these realities together. And with all that knowledge now in your head, you know more then 99.9% of the world about electrons.

=====Credits=====

This episode of Crash Course Chemistry was written by myself, filmed and directed by Michael Aranda, who is also our sound designer, and edited by Nick Jenkins. The script was edited by Blake de Pastino an Dr. Heiko Langner. Katherine Green was our script supervisor and our graphics team is Thought Cafe.