Prof. Russell Stannard: The questions on everyone's minds
The Nature of Matter

Russell: Keep this up, and what do we end up with - apart from a piece of apple too small to bother with? What in fact is everything ultimately made of? It was once thought that the answer was atoms - atoms: the fundamental building blocks of matter. In fact, the name 'atom' means 'that which cannot be cut'. Which is hardly the case. Atoms have an inner structure. It consists of a central nucleus surrounded by tiny particles called electrons. The nucleus has a positive electric charge, the electrons a negative charge and it's the electrical attraction between these charges that holds the electrons close to the nucleus. Electrons are considered to be truly fundamental. They really are one of the basic building blocks of the matter we see around us. The nucleus? Is that fundamental? No. It too has an inner structure. It's made up of neutrons and protons. The neutron and proton are very similar to each other it's just that the proton carries a positive electric charge whereas the neutron has none. It's the charge on the protons that gives the nucleus as a whole its positive charge. But you might be thinking, 'Hold on. Won't the nucleus blow itself apart you know the protons they all have positive charge and as everyone knows, like charges repel? No. Things are more subtle than that. Okay here I have two protons right?
I'm going to push them apart, that represents the electrical repulsion. But they don't separate. Why? Because there's another force at work, an attractive force. In the nucleus the second force is called the strong nuclear force - strong because its more powerful than the repulsive electrical force, and that leads to an overall attraction holding the nucleus together. So, are the neutron and proton fundamental - like the electron? No. When you look inside them you find that they are made up of tiny, tiny particles called quarks - a bit like the pips in the apple. Two types of quark. What we call the up quark and the down quark – which we denote by u and d. The proton has two ups and a down and the neutron two downs and an up. So both the proton and the neutron are made up of three quarks each.
Quarks, like electrons are believed to be truly fundamental. They mark the end of the line. So, everything we see around us is made up of two kinds of quark up and the down, together with the electron. And to this we need to add a fourth particle: the neutrino. Neutrinos are produced, for example, in the nuclear reactions going on in the Sun. The neutrino is like the electron except that it carries no electric charge and so it doesn't experience the electrical force. And like the electron, it doesn't experience the strong nuclear force either. That's only felt by the quarks. But it does experience what we call the weak nuclear force, that's a force responsible for, well for certain kinds of radioactivity. So because they experience only this weak force, neutrinos are famous for hardly interacting with anything at all. 100 billion solar Neutrinos can pass through my thumbnail every second, and I don't feel a thing. So, there we have it: The four constituents of matter: the up and the down quark, the electron and its neutrino. What could be simpler? Except that it's not that simple! No, it's much more... interesting.
This is the Large Hadron Collider at CERN, it accelerates protons round in a huge circle. Two beams travelling in that tube, going in opposite directions – one counter clockwise and one clockwise. And at various points they are made to collide. Why? What's it all about? Are we trying to break open the proton into its component bits – you know those three quarks? No, that might have been one of the original motivations but actually something much more intriguing than that happens. Two protons right? They come together and collide. Hey Presto: an extra particle, a particle that wasn't there before the collision. That's right. A new sub-atomic particle, new matter being created. But didn't we learn at school that matter can be neither created nor destroyed? Yes and that's still true. You can't create new matter out of nothing. But that's not what we're doing here. No, this new matter arises from the energy brought into the collision by the original bombarding particles. It's a consequence of Einstein's famous equation E = mc2 . What this is saying is that matter is a form of energy - a locked-up form of energy. Some of the original energy of motion, E, has now been transformed into this locked-up mass, m. One of the major tasks of high energy physics is to identify what kinds of new particle can be produced. The more energy available in the collision, the heavier the

particles we can produce – hence the insatiable drive for building bigger and bigger and more powerful accelerators. And what we find is that some of these new particles carry properties that ordinary matter doesn’t have - properties with quirky names: strangeness, charm, top, and bottom. I myself had the privilege of belonging to the international collaboration that was the first to make a direct sighting of a particle carrying charm. Like the proton and the neutron, these new particles are made up of strongly interacting quarks. But because of these new properties, the new particles can't all be made up of just the two types of quark that we've been talking about so far, the ones that make up the proton and neutron.

No, we need to add more fundamental particles - different quarks – quarks that do carry the new properties we've found. One carrying charm, one carrying strangeness, one for top and one for bottom. And to further complete the picture we have to add additional fundamental particles, which like the electron and neutrino, don’t experience the strong nuclear force. The muon and its neutrino, the tau and its neutrino. So that’s it, three groupings of four particles, each of these groupings called a generation. Three generations, one, two and three. These are the ultimate constituents of all the matter we see around us, plus all the more exotic types we create in these high energy collisions. Unravelling all this has been a wonderful achievement. But we're still left with some worrying puzzles. Three generations. Why three? Why not just one? Or, if you’re going to have more than one, why not an infinite number? What’s special about three?

Then there are the masses of these particles. What determines the values of their masses? And their masses are very odd. The tau particle for example is 3520 times heavier than the electron! As for the neutrino, they are so incredibly light for a long time it was thought they had no mass at all. As for the quarks, well the top quark weights 50 to 100 thousand times as much as the up quark. Why? You know, why these huge differences in mass? What does it all mean? We simply don't know.

In fact, in order to make sense of our understanding of the nature of matter and the forces between them, we need to feed in by hand the values of 19 different parameters. And we have no way of justifying theoretically what any of those values ought to be. Being a high energy physicist myself, it remains my hope that one day, some day we will be able to find answers to these outstanding questions. But I can't help wondering how close we might be getting to the Boundary of the Knowable.

After piece

Tony: Okay everybody.

Russell, I know high energy physics is your thing. But do you have to devote so much time to it?

Russel: Yes!

Tony: Can't we cut it down?

Russell: No. No, you should thank your lucky stars that I was as brief as I was. I haven’t mentioned anything about the Higgs Boson, everybody knows about the Higgs Boson or heard about it but I haven’t said anything about that. I haven’t said anything about grand unification of forces, why do we believe that there are only three generations?

Tony: Fine.Russell: supersymmetic partners, I haven’t mentioned that.

Tony: Okay fine.

Russell: And the magnetic monopole.

Tony: Yeah. Russell: You know, where, where, I’ve hardly started Tony.

Tony: Okay, okay. Okay, fine. Moving on everybody.