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Extreme engineering

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Thank you very much for the introduction and for the invitation and opportunity to deliver The Royal Society of Edinburgh and The Royal Academy of Engineering Annual Joint Lecture.

I love music. Forty-three years ago when I got married I purchased the very best hi-fi system available but I found it uninvolving. Even changing all the individual components in the system didn’t yield any fundamental improvement. I started to explore why it was so unsatisfactory and discovered that the turntable was being influenced adversely by the changes in sound pressure from the loudspeakers. I established this fact by simply putting the turntable outside my living room and listening with the signal leads to my system passing underneath the door. It sounded much better and much more musically accurate and involving than when the turntable was located in the same room. This experiment only took a few moments to set up, followed by a quick listen.

At that time I was working for my late father’s engineering company, so I set out to use that wonderful resource to make a turntable that wasn’t influenced adversely by the loudspeakers. One thing led to another and, with the assistance of my father, who designed a very quiet-running central bearing, and my very supportive skilled colleagues, I succeeded in making an LP record playing turntable that was immune to acoustic feedback from the loudspeakers. It was also precision engineered to very high standards to enable more music information to be extracted from the record groove. In a hi-fi system the music playing source product comes first and no amplifier or loudspeaker can improve on its input signal quality. My turntable could improve the sound of any system and my company Linn Products was founded to make this revolutionary product.

My turntable excited and thrilled those who listened to it but news about its revelatory performance also aroused great scepticism among those who thought they understood all there was to know about hi-fi. Claims that a turntable could improve the sound of a system were initially dismissed by some hi-fi experts as being unbelievable. Some hi-fi retailers would not even listen to my turntable to determine if there was any truth to my claims, even although it would only have taken them a few minutes to discover for themselves. Conventional wisdom was that the loudspeakers were the most important components in a hi-fi system because that is where the sound comes from. I was told that the turntable just goes round and round. I replied that loudspeakers only go in and out! Experts can be wrong. The fact that I knew very little about hi-fi had led me to examine all the relevant issues with an open mind and so I embarked on a learning journey which led to the development of transformational products.

The turntable I made, which I eventually named the Linn Sondek LP12, looked the same as most other turntables but almost every component had a different purpose. I had optimised the suspension for acoustic isolation instead of shock resistance. Similarly, every other component in the product also had an alternative focus. In combination they operated to allow more of the precious musical information in the groove of an LP to be recovered and then converted into the delicate electrical signal that could be amplified to drive the loudspeakers. The integrity of the recording process meant that the smallest information it captured in a record groove is smaller than the wavelength of light, and the smallest electrical signals generated comprised only a handful of electrons. However, the record...
playback process had great scope for loss and I was aware that it was impossible to ensure a perfect result. So I designed my turntable in a modular way, doing the best I could at the time, but also so that all the key elements could be developed and that improved parts were then retro-fittable. Our existing as well as new customers could benefit as our knowledge and capability improved. A modular, upgradeable and expandable system architecture fostered sustainable long-term relationships with our customers, but above all it encouraged and facilitated learning and so enabled Linn to give our products the longest possible competitive model life. Customers built our business so we look after them. We still make the Linn Sondek LP12 turntable, and although every part has been improved we can still service and support past customers using current parts. Not only does this reduce the need to stock obsolete spares, but after a service, repair or an upgrade the performance of the customer’s system can be improved.

I also devised a single-stage manufacturing process to replace the conventional production line so that instead one responsible person performed an entire intelligible task from start to finish. To conceive and test this concept took only 30 minutes, and to engineer this radical operational reform and change to the single-stage build methodology we still deploy at Linn took only a few weeks. If one person can assemble a complete product then another can service it, and so again we benefited from the fact that in life one good thing often leads to other good things. Our strategy of selling by comparative demonstration meant that we had to outperform our competition.

To achieve this we needed to use our people at the highest possible level. So we gave them responsibility and used open standard interfaces that exposed us to competition. All this incentivised us to keep on learning and maintain an enthusiastic interest in our work.

I soon found that we needed better loudspeakers to demonstrate our turntable. I wanted to make a Linn loudspeaker that could more accurately reproduce very low frequencies but when I expressed this intention I was told it was impossible, for two reasons. First, I knew nothing about loudspeakers and so could not possibly achieve something so ambitious; and second, something so obviously desirable, if it were possible, would have already been done. But the second notion if it had been true would have meant that nothing better could ever be achieved. And as for knowing nothing about loudspeakers, that was almost true but I knew that in two years time either I would know more or less everything about loudspeakers and would have failed, or I would have succeeded but still not know enough about loudspeakers.

In the event, I came up with a novel concept which enabled us to achieve our objective surprisingly quickly. In fact it took less than a week to conceive a workable idea and prove it had potential with a prototype. So the impossible didn’t take very long. Just trying to do something that had not been done before appeared to make it almost certain that a way could be found. In fact all I had to do really was think differently. Most good ideas are obvious in retrospect, while in prospect they seemed counter-intuitive or impossible. Just examining the alternatives to perceived wisdom is one way of acquiring new understanding and achieving unprecedented success. There are an infinite number of undiscovered useful possibilities in our universe and our short engineering journey has only exposed a tiny number. Today our company applies the same principles that we applied to analogue sound components to get more information from a digital data stream, and we have improved every component in the audio reproduction chain with original performance-led designs that sell very successfully around the world.

An innovative idea occurs in the mind of a single individual, but interaction with others and with problems and challenges and the things that surround us never fails to stimulate or improve new ideas. In fact, all imaginative thought requires interaction, within ourselves, with others and with our surroundings.

A new idea, like a new product, starts off like a new baby, having a separate and distinct identity, and even if its body, personality and character are still unformed it can exhibit great potential. For these reasons fairly rudimentary and even crude experiments, prototypes and products can be revolutionary in their impact, yet not too difficult to develop, deliver or sell using existing resources. So the barrier to entry is less than normally imagined, and can be minimal. Indeed, no matter how complex or advanced a new technology is or becomes, new start-ups can and do appear and new innovations, including even the most radical, always emerge, as ever, from the inspired individual mind of a single curious and motivated human being.

In pursuit of integration and flexibility we work together in a learning company, with a flat egalitarian organisational structure using a team approach to achieve more by working together than we could as isolated individuals. Our goal is always to maximise individual understanding and achievement.

For Linn to be successful at what we care about most, which is giving people pleasure from pitch-accurate sound reproduction, almost everything we make is generated in-house. We devise or control every aspect of our design and manufacturing processes. We manufacture all our key components, from machined metal parts to electronic circuit boards, and we write or control every line of code in our software. We deal with mechanical, electrical, acoustic, recording and industrial engineering, analogue and digital electronics, embedded and user interface software, production and test engineering, ergonomics, product styling, and a whole wide variety of other related disciplines. We write our own product test software and even all our own website and business systems software in-house. We do
all this ourselves to ensure that a Linn sound system is a transformational purchase that will change and improve our customers’ lives. Our products are Clyde-built to last, and are also designed to evolve and develop.

Engineering is about making things to a standard. It is about shaping our world and behaviour, not just objects. As imaginative tool-wielding animals we have evolved, from vulnerable creatures that would break nuts or bones with a piece of rock to feed or to defend ourselves, to the creators of all kinds of tools, ideas and things that were not dreamt of only a generation or so ago. Yet despite such amazing progress we still cannot imagine what life could be like for our children’s generation let alone further ahead in the future.

Even with all our progress at Linn there is still a vast gap, although it has narrowed considerably, between real natural performed live music and how accurately it can be recorded and reproduced. All this is despite the fact that in our Linn D5 digital streaming sources, which have replaced CD players, the clock generator devices have timing variations called jitter in the region of only seven picoseconds. A picosecond is a million millionth of a second, and by comparison light can travel only two millimetres in seven picoseconds. These devices also have some sensitivity to acoustic pressure, so we have to shield the components and avoid exposing them to sound and vibration to avoid any degradation in their jitter performance. You would imagine after so much time, effort and passion with this kind of extreme engineering that we must be delivering perfection, but that is far from the case. Not only are we working to ever-higher standards and making bigger improvements than ever, with every sign that this rate of progress is accelerating rather than slowing down, but any difference we do make, no matter how small, can be clearly detected by a discerning listener, such are the amazing powers that all hearing human beings possess and share.

I want you to participate in a short demonstration. I am going to ask you in a moment to do something for me. I am going to ask you to touch your neighbour, but I want you to preferably touch someone you didn’t come here with, so please if possible pick someone sitting close beside you that you do not know. Please do so now.

As you all just experienced and demonstrated, we are hesitant to touch someone we do not know. In the situation that I have constructed what people do is that they normally touch the back of the stranger’s hand. They quickly make contact and then they hold that position. We do this because we become conscious of something we don’t usually consider and that is that touch can be a communication that might give rise to embarrassment or confusion. For that reason we make contact quickly and then hold the position. We realise that in the brief instant of the transition period as we actually make the contact, a touch has the capacity to express and transmit our feelings. In fact, the briefest touch can communicate a diverse range of feelings and emotions. Music is a universal language of human feeling and emotion. It is sung, written and performed by people for people. Music is the song of our species. It is in our DNA. We all respond to music in the same fundamental way. Human beings all around the world, irrespective of culture, can experience the same kind of elemental emotion and feeling from a piece of music. No one confuses a happy tune with a sad one. We all share a musical vocabulary covering the universal and basic human emotions of excitement, love, hate, fear, lust, passion, anger, remorse, anguish and so on. These feelings can be communicated by short phrases contained within music that we call micro rhythms. They are of very short duration, typically between 5 and 15 microseconds. A sound frequency we can hear reflects its rate of change of pressure if instead of being exposed as a listener to the frequency waveform that we hear, we are exposed to the corresponding pressure wave form that we can feel directly, for example by physically applying pressure on to, say, our forearm, we also respond in the same identical way to the same emotional vocabulary communicated by the same micro rhythms.

We all experience the same emotions when they are communicated by the same shape of signal because the language of feeling and emotion that we call music transcends all boundaries of race, culture, age, intelligence, education and so on; indeed it extends across the barriers of time so that when we listen to music by Mozart or Beethoven being played we can experience the emotions that the composer intended us to feel and that the performing musicians are able to communicate. Our ears are directly coupled to our brains. When we are transported by the pure sound of natural live instruments playing music, without the distorting influence of the hardware with its microphones, amplifiers, loudspeakers and so on, the mechanism that transports us is the fact that it is perfectly easy to simultaneously reproduce every sound we hear as it happens and so we can transfer that sound to our own brain without any conscious effort. Indeed people with sufficient skill can actually experience the sound of a piece of music by simply reading the score and consciously generating the sound of the music in their own head. The generated electrical signal in their brain can be detected. The sound they generate corresponds to the sound that we would all recognise as being the sound of the live music performed from the same score.

We are all familiar with the concept of perceived colour being a combination of different frequencies of different amplitudes. By mixing separate colours in different quantities we change the net result. We know white is a combination of all the colours of the rainbow stimulating our eyes in the correct proportion. If we change the frequency (in other words the colour) or the amount of any these components (in other words the amplitude of any one of the frequency components), we will change what we see. The same scenario applies to sound. A note in music is not like laser light, a single frequency with a single amplitude. Like most of the colours we see, music is made up from many different frequency components comprising the fundamental generated by the instrument and its various harmonics, each with its own amplitude. Together they combine to produce a net resultant sound effect which we perceive as the pitch of the particular sound or note or chord in question, and of course we often listen to many musical instruments playing at the same time. These beautifully engineered and highly evolved devices have been designed, crafted and developed to give us as rich and complex a tone as possible and to amplify the level sufficiently to travel long distances or fill large spaces.

Each skilled assembler is responsible for making a complete product.
If, when we reproduce music, any of the frequencies generated are shifted or if any of their amplitudes are altered inconsistently, then the net resultant pitch will also change. So if a hi-fi system has the ability to change the value of any frequency or its amplitude in a non-linear way it will then differentially change the pitch of every sound being reproduced and that is why we have to go to such extreme lengths to engineer pitch-accurate equipment that can begin to do justice to the unique communicative power of music. Changing the pitch of the notes even ever so slightly means you are changing or even destroying the tune and its meaning.

Such is the sensitivity, resolution and power of human hearing, of our ear/brain combination, that we can detect the smallest differences by listening actively. Active listening is a deliberate, conscious, mental process where we try to mimic every sound we hear. If you are concentrating and listening attentively to me speaking, then you are repeating every word I say simultaneously but silently in your head. Listening is defined as silent repetition. All of us have an expectation of what music is. All of us have an internal music reference. All of us can spot a mistake or a wrong note. This internal reference makes our hearing unlike our vision or taste or other senses because it is fast, accurate, consistent and universal.

If, when we try to follow reproduced music, we find we cannot easily do so, it is usually because we can locate one element of the sound something else has occurred, and no subsequent tone or note is certain or correct enough for us to speedily locate and mimic. The smallest inconsistencies and pitch errors matter greatly to us because they disrupt our ability to continuously follow and so respond to music. Extreme engineering precision is required to do justice to the challenge of reproducing recorded sound convincingly. With better, more pitch-accurate reproduced sound that more closely resembles real live music we can readily locate and follow more of the notes, instruments and elements of the music more of the time in the same natural way that we do with live music. We can do this because it matches closely with what is expected and conforms to the internal music reference we all have embedded in our DNA.

The earliest known example of a precursor to human beings and indeed to all the vertebrates, is a small two-inch long wormlike creature, whose fossilised remains were discovered in the Burgess Shale in Western Canada over 100 years ago. The circumstances pertaining in the Cambrian period starting around 550 million years ago facilitated an amazing explosion of life, in a vast array of diverse forms, and some of these soft-tissue creatures were fossilised and preserved. The conditions existing at that time that gave rise to this particular worm had also led to a great many other varieties of new life forms, in all kinds of strange and unfamiliar shapes and arrangements. All the unfamiliar forms then perished over time in a process of mass extinction. This evolutionary process has eliminated developments of almost all the varieties of life that were included in the examples we have of all those frozen in time in the Burgess Shale.

That wormlike creature, an example of the predecessor of the vertebrates, that was found there and which survived the process of mass extinction we call natural selection, went on to develop into all the vertebrates that remain on our planet today. Consider what senses our earliest known ancestor might have possessed. It had no eyes so it could not see. It had no hands or fingers it could use to touch. It had no nose so it could not smell and without a tongue it could not taste. It had no ears so could not hear, but we are compelled to believe the one sense it must have had was pressure sensitivity. Without pressure sensitivity it is not possible to maintain a position against gravity, current, or wind, in water or on land or in the air. Without pressure sensitivity we cannot balance or move, we cannot feed, seize prey or move away from our effluent; we cannot avoid a predator, swim, shool with our brethren or mate and reproduce. So pressure sensitivity is a most fundamental sense. That wormlike creature still exists. Our ancestor lives on inside every one of us as our spinal column and the primitive limbic core of our brain. Just like a tadpole develops arms and legs to become a frog, our wormlike ancestor which emerged in the Cambrian period did the same. In that sense we have all evolved from pond life and are creatures of the sea.

As our senses and capabilities evolved we began to communicate by singing to each other in the same way that whales, dolphins, chimpanzees and birds sing to communicate. Our spoken natural languages have evolved from song, and as they grow apart they diverge to separate us into language groups. Two thousand five hundred years ago probably less than a thousand people spoke Latin. Today a billion speak some derivative language, but a Romanian cannot understand an Argentinean. But, because music is the song of our species, the underlying language of music is a constant and remains universal. Music would be just a stream of noise except for the fact that we can package it into meaningful elements like notes, which according to their perceived pitch occupy a position in a scale of frequencies we recognise and order across our hearing range. Tiny micro rhythms allow us to locate, discriminate and respond to each element. Spoken languages have evolved from music, and like music they are also just a stream of noise. If you listen to an unfamiliar foreign language being spoken it certainly sounds like a stream of noise.
To learn to understand otherwise, we have to laboriously memorise several hundred common words like mummy, daddy, cat, dog, etc, and learn their meaning. What we are really learning, however, is how to recognise and identify the leading edge waveforms of each word. If I say, “would you like a glass of beer?” you probably recognise and can anticipate each word before I have pronounced it fully by recognising its characteristic leading edge waveform and anticipating what might follow. Once we can separate the sound of a foreign language into the meaningful packages we call words, we can then compare them with our own internal reference, our own individual language dictionary, to see if we recognise them or not, and then enquire about and learn the meaning of those words that are unfamiliar.

When a skilled pianist or violinist or flautist plays music, the feelings and emotions they seek to express can be communicated in every touch of each key; in every breath they take, in the leading edge waveforms of the sounds made by every string or bow they pluck, and in every micro rhythm they express within the music. This is all communicated through the air for us to receive, and we then experience and feel the same emotions as those that were expressed. Difficult as that may be to believe, what it makes clear is that music is touching at a distance. Considering this capability confirms the understanding that we are fundamentally pressure-sensitive creatures. Pressure sensitivity shaped our evolution, formed our identity and determined our capacity to survive. Pressure sensitivity gave us the power to move and informed us whether we were swimming up or down and indeed created the possibility for that choice. The power to choose in turn compels us to think and to learn, and thinking and learning and action lead to knowledge, understanding, communication and cooperation. Music is consistent with a three-dimensional navigation system and it goes perfectly with movement whether it is swimming, running, cycling or dancing. And this internal and external motion is the imperative for feeling, creativity, imagination and love. Each and every one of us exists because a single tadpole-like egg, which then developed into a foetus floating and swimming in the salty water ocean of our mother’s womb. The first sense we develop is our sense of hearing by 14 weeks, and the first sounds that we hear are the sounds of our mother’s heart beating, then the outside world and the rushing of blood, and eventually identifying our own heartbeat and creating our own sense of identity. All of us are creatures of the sea. All of us are shaped, formed and born as pressure-sensitive creatures. All of us have experienced the entire evolutionary journey of our species. Pressure sensitivity is embodied into each and every individual cell in our body which all vibrate and respond to changes in pressure. We are all pressure-sensitive organisms responding to the complex pressures and rhythms of life and the universe.

Pressure is applied force, action causes reaction, and the capability to apply force through a distance gives us the energy to perform work, to act and cause action and make things happen. Being pressure-sensitive, interactive and applying forces by singing and dancing, or pushing and pulling is at the heart of our nature and our evolution, and is the source of our tool-wielding ability and our capacity to think and shape our existence and shape our world. The forces applied and that we are learning to apply range from the smallest to the largest. Pressure sensitivity, from the individual cellular level to across our complete body, and the development of our ability to respond to and shape our world makes all productive life engineering. Every field of human endeavour allows infinite scope to understand more, explore further, push forward beyond established limits, find opportunity to improve, and to originate and innovate in every set of circumstances and so to shape, improve and indeed to engineer every aspect of our lives for the better.

By engineering improved individual and group productivity we create and increase wealth for ourselves and our species. So I would ask you to reflect upon the fact that if there were any single discipline, practice or activity without which we could not imagine sustaining our rich life, it would undoubtedly be engineering. Nothing has greater importance or is more fundamental to what we are and our future. To discover the art of engineering is to live and shape your life to the full with intelligent productive actions and to shape and touch the lives of others.

The intention of this annual engineering lecture is to inspire people with engineering. You are all wonderful. Inspire yourself.

Thank you for listening.
The Royal Society of Edinburgh

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