EVERYBODY HERTZ

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The Amazing World of Frequency, from Bad Vibes to Good Vibrations

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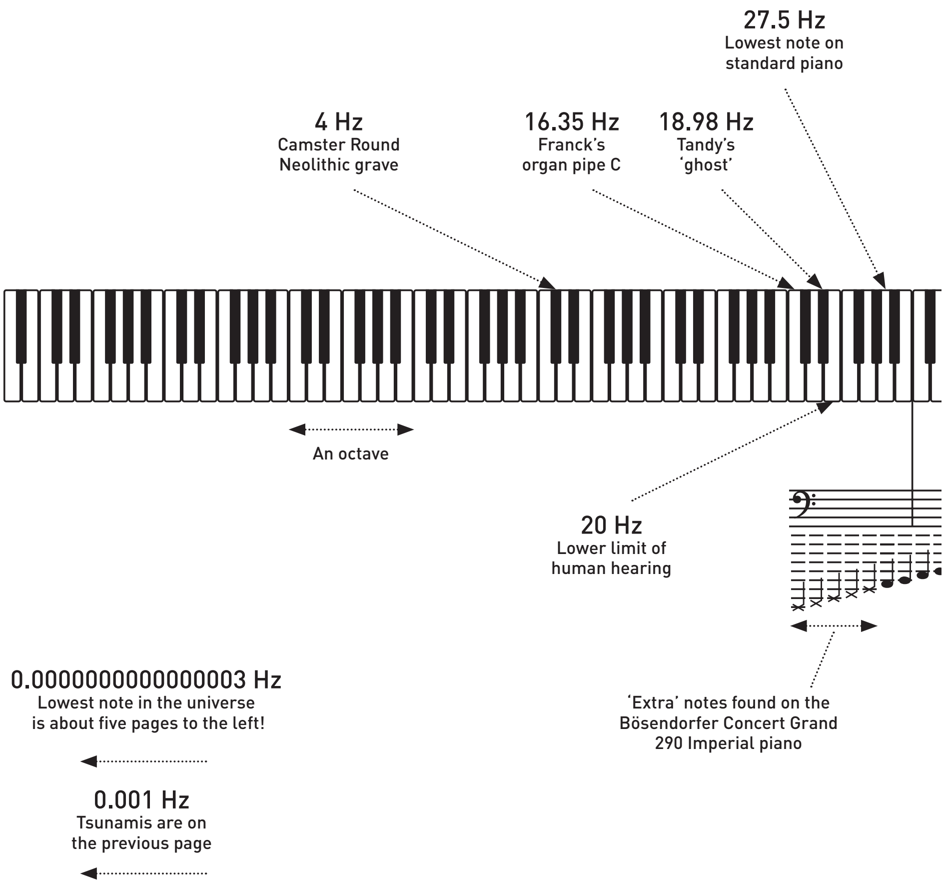
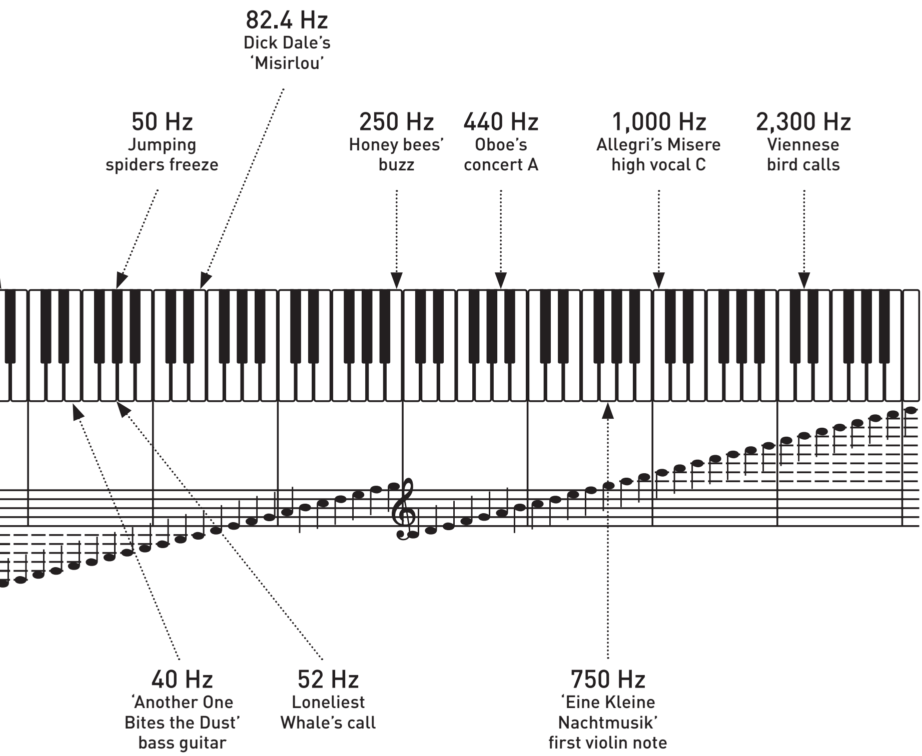
The Key


27.5 Hz
Lowest note on standard piano
4 Hz
Camster Round Neolithic grave
16.35 Hz
Franck's organ pipe C
18.98 Hz
Tandy's 'ghost'
An octave
20 Hz
Lower limit of human hearing
'Extra' notes found on the Bösendorfer Concert Grand 290 Imperial piano
0.0000000000000003 Hz
Lowest note in the universe is about five pages to the left!
0.001 Hz
Tsunamis are on the previous page

1,000,000,000,000,000,000,000 Hz
Gamma rays about six pages
to the right!

20,000 Hz
Upper limit of human hearing, just over
three octaves away on next page



A♭
Prelude

In the days leading up to 14 November 1940, British intelligence mixed up two musical notes (the two found at the start of the vocal line of the swing song 'La Mer'). The consequence was that, on the morning of 15 November, the English city of Coventry suffered one of the worst bombing raids of the Second World War. It is impossible to say how many lives could have been saved had the notes of G and C been correctly identified.

Allow me to explain.

In the deadly skies of 1940, the German military were technically far superior to the Allies, and one of their greatest secret weapons was their inspired radio guidance technology. Thanks to the Lorenz system invented in Berlin in the early 1930s, aircraft could land guided by precise radio beams, dispensing with the need for visual contact with a runway. With some minor modifications, the Luftwaffe initiated the *Knickebein* project, an ingenious adaptation of the Lorenz system which guided their bombers along two almost parallel radio beams, one of dots to the left and the other of dashes to the right. If a pilot could fly perfectly down the bowling lane between them, he would hear a mix of these dots and dashes as a single continuous tone, directing him towards a specified bombing target. Drift to the left and the continuous tone was replaced by dots; drift to the right and he would hear only dashes. Thanks to *Knickebein*, neither clear conditions nor daylight were essential for successful bombing raids. The beams were transmitted from Nordfriesland near Germany's border with Denmark, Kleve near the Dutch border, and Lörrach in the south-west. But in 1940 very few in the British military believed the Germans had the technology to send highly accurate radio beams from continental Europe over English skies.

A 28-year-old PhD science graduate from Oxford begged to differ. In 1939, Reginald Victor Jones had been the first scientist ever assigned to British intelligence. In 1940, he found himself – as Assistant Director of Intelligence (Science) – bending the ear of Winston Churchill at 10 Downing Street. He told the Prime Minister that the Germans had constructed aerials he suspected could broadcast two radio signals from the same location, remaining only yards apart at their ultimate target in England – like a very narrow torch beam. This would allow German bombers to navigate along such beams, dropping their lethal cargos with frightening precision.

Churchill had a hunch that R. V. Jones was something special. Undeterred by the scepticism of his military bigwigs, he gave the young man permission to put his theory to the test. An aircraft searched the sky listening for the theoretical beams, and eventually, after some early failures, pilot Flight Lieutenant Bufton and his observer Corporal Mackie found them. Jones was informed that the Germans were broadcasting 1500 hertz (Hz) dots and dashes, the musical note G_6 (found at the end of Tomaso Albinoni's 'Adagio in G Minor' – I'll explain what G_6 means shortly).

Jones now had a dilemma. If the RAF and ground defences ambushed and destroyed the German bombers flying in formation along the *Knickebein* line, the Nazis would know that the British had rumbled them. It seemed like there was no choice but to let the Germans fly on undisturbed. Jones opted for a more wily approach, broadcasting a rival British G_6 note of 1500 Hz, one that intersected the Germans' signal but aimed away from the Luftwaffe's intended target. If the bombers could be fooled into following the British G_6 tone, they could be guided to drop their loads in much less densely populated or strategically sensitive areas.

Jones was justifiably very pleased with himself. He had proved that the Germans' *Knickebein* project was real, that they were broadcasting radio beams across English skies, and that there was potential to blunt the Luftwaffe's attack via a 1500 Hz counter-tone. Using information gleaned from the codebreaking Enigma machine, British intelligence predicted that night-time bombing raids were soon to target cities in the Midlands, particularly Coventry and Birmingham. Churchill's bigwigs had to stand aside whilst Jones, the young genius of British intelligence, led the innovative newfangled defence against the might of the German Luftwaffe. But all was not well; the bombs still fell on Coventry.

Jones wrote about the discovery of the two-tone mix-up in his spellbinding 1978 book *Most Secret War*:

> the Royal Aircraft Establishment at Farnborough found that the filter [in a shot-down German bomber] was tuned to two thousand cycles per second, a high-pitched note corresponding roughly to the top 'C' on a piano. Our jammers had been set not on this note but on one

> of fifteen hundred cycles per second, corresponding to the note 'G' below top 'C'.

The Germans' note was actually a C at 2,000 Hz and not a G at 1500 Hz. Indeed, their radios had even been set to filter out any notes beneath this. This meant that the British had been trying to fool the Germans with the wrong note; the bombers' radios never even heard the British counter-beam.

In his book, Jones uses a rather inventive musical means of explaining his story, illustrating the frequencies of the two radio signals with corresponding notes on a piano. Understanding that the British were 500 Hz away from the 'correct' frequency is of interest, though a little meaningless to the reader. However, knowing that the mistaken pitch was a mere three piano notes away from success gives us a clearer sense of why Jones was so exasperated by the failure. 'Of all the measurements in connection with the German beams, easily the simplest was to determine the modulation note [the 1500 Hz tone],' he wrote, 'and yet whoever had done it had either been tone deaf or completely careless … I was so indignant that I said that whoever had made such an error ought to have been shot.'

It seems that Jones' brilliant mind knew no bounds. As well as spotting cunning Nazi technological innovations, Jones, the author, had an ingenious way of simplifying the complexities of frequency, combining the often-meaningless unit of hertz with the much more familiar concepts of musical pitch and a piano keyboard. In homage to Jones' creative and illuminating trope, *Everybody Hertz* will extend his concept, exploring *all* frequencies within a musical context, using the familiarity of a piano keyboard to help us understand, hear and marvel at the extraordinary world of vibration, waves and frequency.

Here's a quick test for you: sing the note of the frequency 123 Hz. I assume you're struggling. It's probably easier if I reveal that 123.47 Hz is the first guitar note of the Rolling Stones' '(I Can't Get No) Satisfaction'. How about 392 Hz – can you hum that? Again, it's far more achievable if you know that 391.99 Hz is the pitch of the initial three Gs played by the violins at the start of Ludwig van Beethoven's Symphony No. 5. When presented with musical examples, your memory can give you an approximate equivalent tone for that frequency. Such aural signposts will feature throughout *Everybody Hertz*, providing musical reference points for our fascinating journey.

However, frequencies are not exclusive to the range of a piano or even the spectrum within which music lies. Above the highest piano C at 4,186 Hz (this is C_8, numbered so because it's the eighth C you encounter from left to right on a standard piano), frequency continues to rise through the ultrasonic range, as well as through microwaves, X-rays and gamma rays. And beyond the lowest bass note, measurable vibrations descend forever. But what if a piano could extend its range to cover all of these frequencies? If the ivories continued beyond that top C, where would those imaginary notes lead to? As light is a wave with a set of frequencies, how far along a piano keyboard would one have to travel to 'play' a rainbow? And what would it sound like? Similarly, how many octaves to the left of a piano's bottom A at 27.5 Hz (frustratingly not numbered A_1, but A_0) would one have to plunge before one could find the notes of tsunamis and earthquakes? Welcome to my new invention – the Infinite Piano.

As a space-obsessed child (I persuaded my parents to let me skip school to watch the first Space Shuttle launch live on TV in 1981), I dreamed of donning a tinfoil suit and exploring the mysteries of the universe. When I lowered my gaze (and ambition) and decided to become a musician instead, little did I know that the cosmos would one day come to me. Could it be that all the violin vibrations which first resonated through me as a 5-year-old, and which have continued throughout my professional life, inspired my interest in frequency? Or perhaps my compositional exploration of new and extreme sounds and pitches sparked a desire to search beyond the limited horizon of a 'normal' piano's range? Whatever it may be, my study of the narrow spectrum of mechanical vibration that is music has led me to create an instrument which puts the universe at my fingertips, dispensing with the need for an external oxygen supply or a billion-dollar spaceship. Call it compensation for the fact that I never got to ride a rocket, or even see that first Space Shuttle launch – it was delayed for a few days, and there was no chance of getting a second day off school.

Before we experience a piano scale like no other, though, it might be best to clear up some important questions. Firstly, what is 'hertz'? Frequency used to be measured in cycles per second, a cycle being one complete oscillation of a wave – if the duration of this was one second, the old nomenclature would call that one cycle per second (1 c.p.s.). In 1935, the International Electrotechnical Commission renamed this measurement in honour of the man who proved the theories of electromagnetism, Heinrich Hertz. And in 1960, hertz (Hz) was adopted in the International System of Units as an official unit of frequency; one cycle per second was now 1 Hz.

Secondly, what is a wave? Physics textbooks will tell you that it is the transmission of information or energy from one place to another, without any material object making that journey. I prefer to explain a wave using the classic kids' game 'Telephone', where a whispered message is passed along a line of children. As with a wave, information is transmitted without anyone moving. However, it's not much of a game if the first child walks to the last child and whispers the message – and it's no longer an example of a wave either. *Everybody Hertz* will focus on the two main types of wave: mechanical and electromagnetic.

The sound of the German dots and dashes of *Knickebein* were made through *mechanical* waves, regular changes of air pressure generated by the pilots' headphones, in turn vibrating their eardrums 2,000 times per second (2,000 Hz), the note 'top C'. Light is also a wave, but not a mechanical one – it does not rely on air pressure to travel. It is an *electromagnetic* wave, propagated via atoms and the space in between them – it can travel through a vacuum. For example, red light is a form of electromagnetic wave with a frequency around 430,000,000,000,000 Hz. This means that the wave is vibrating 430 trillion times per second, a little faster than most of us can comprehend.

But even the awesome frequency of such a complex, non-sounding wave holds no challenge for my Infinite Piano. It is an ingenious and non-discriminatory instrument. It cares not whether a wave is mechanical or electromagnetic, whether it is audible or silent – it can play all types of waves at all frequencies. But can it truly be called an *infinite* piano? Is there a limit to vibration? Certainly, as it is possible to halve a hertz number forever, we are good-to-go down at the bass end of our piano. Many eminent physicists claim there is no theoretical upper limit to frequency either – and who am I to disagree? So perhaps my piano really is infinite.

The impact of frequencies upon us humans is staggering. We're shaken by mechanical waves, enabling us to hear and feel. Our brainwaves generate frequencies that change throughout our waking day and our sleep. We see vibrations in the form of light, we crave the frequencies of radiation emitted by fire and the sun which give us warmth. Different parts of our bodies have different resonant frequencies, enabling us to see ghosts, or forcing us to hyperventilate during blockbuster movies. And we rightly try to avoid the ultra-high frequencies of radiation which can severely damage our bodies – unless we need an X-ray or cancer treatment, in which case those same frequencies can be incredibly beneficial. It is also fascinating to explore the impact of frequency upon everything else on our planet, and even beyond. All living things, from rats to elephants, rely on vibrations. To eat or be eaten is often a matter of a single frequency – if your predator's hearing is specifically attuned to the frequency at which your wings beat, you might be in trouble. From communicating where the next meal is to drumming out a courtship dance, from plucking the strings of a finely spun silk web to navigation via the micro-vibrations of the mountains, living things rely upon hertz.

Cats, as it happens, are the perfect living subjects for this preface. Studies have shown that they purr at 25 Hz and 50 Hz – the musical pitch of A♭. I was initially a little sceptical of this, until I listened to my own cat … and yes, Cysgu (pronounced 'Cusky', the Welsh word for 'to sleep') purrs at around 50 Hz. A couple of questions that have perplexed scientists are how and why cats purr. The latest theories suggest, as most of us would have probably guessed, that purrs emanate from a cat's larynx. But *why* they purr is a much more difficult question to answer. Though a purr seems to exude an infectious state of calm and contentment, some cats also purr when they are stressed or anxious. And some purr more often than others – some when they want food, some even when they are eating. But researchers are generally in agreement that the purr of cats (and not only the domesticated type) is centred around 25 Hz or 50 Hz.

There is a rather left-field theory that the purr is a self-healing device, promoting the growth of healthy bones and tissue. A recent study concluded that 'low frequency (25–50 Hz) vibration *in vivo* can … repair bone injury'. Using a slightly alarming combination of forty New Zealand rabbits' femurs, bone marrow mixed with a salt solution, and a power drill, researchers found that four weeks after surgery, 'the bone defects were repaired effectively in the groups subjected to vibrations at frequencies of 12.5 Hz, 25 Hz, and 50 Hz. Specifically, bones from the 25 Hz and 50 Hz treatment groups displayed increased callus formation, suggesting these two frequencies promote the best bone fracture healing and recovery.' In other words, the notes of $A\flat_0$ and $A\flat_1$, vibrated on rabbits' bones, increased the speed at which fractures heal. 50 Hz, the frequency of $A\flat_{1,}$ is the second note of the bassline in Queen's 'Another One Bites the Dust' (on the word 'bites'), which is perhaps darkly apt for a story about rabbit experimentation. The next time your cat purrs an A♭, consider this – she could be telling you she's content, stressed, or hungry. Or she might want you to leave her alone as she's in the process of repairing her bones. Cats are so enigmatic.

Though I have promised a journey across the Earth and out into the universe, there are plenty of frequencies to explore at home. Look no further than your fruit bowl. Bananas and Brazil nuts emit frequencies in the electromagnetic spectrum that we would recognise as radiation. Yes, bananas are radioactive. Indeed, there is an informal unit of measurement of radiation known as the 'banana equivalent dose' (BED). Bananas contain a radionuclide, potassium-40, which emits radiation at a frequency between 3,143,400,000,000,000,000,000,000 Hz and 3,530,300,000,000,000,000,000,000 Hz (to play the lowest frequency of potassium-40 on the Infinite Piano, you would have to walk just under 12 metres or 73 octaves to the right of middle C – not that 'middle' could exist on an Infinite Piano). Such radiation, in large doses, plays havoc with the atoms, molecules and cells in our bodies, causing uncontrolled and random cell division, which can ultimately lead to cancers. However, it has been estimated that one would have to eat 10,000,000 potassium-rich bananas in just one sitting in order to do any serious radioactive harm – not perhaps the most appealing lunch.

The chapters of this book follow the notes of a piano keyboard – the white note chapters sound a rising scale through the world of frequency, whereas the black notes explore the subtleties of sound and music, areas which have dominated my professional life.

From the ghostly infrasonic vibrations that smear our vision, through the rumbling 52 Hz call of the world's loneliest whale, to the atomic oscillations of lethal 'Bikini snow', there is so much to learn and understand about the world of frequency. Come, sit on my Infinite Piano stool and fasten your seatbelt as we embark on an amazing ride through vibration and frequency, from the lowest 'note' in the universe through to the astoundingly high frequencies that measure time itself. Our first stop: a black hole.