# newsletter

OF THE JAMES CLERK MAXWELL FOUNDATION, EDINBURGH

Issue No.16 *Summer 2021* Part One

ISSN 2058-7503 (Print)
ISSN 2058-7511 (Online)

# Homage to Heinrich Hertz

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*"In his 1870 Presidential Address to the Mathematical and Physical Section of the British Association for the Advancement of Science, the great Clerk Maxwell spoke of, as an undecided question, whether electromagnetic phenomena are due to 'direct action at a distance' or 'the action of an intervening medium'. The year, 1888, will ever be memorable as the year in which this great question has been experimentally decided by Hertz..."*

Professor G.F. Fitzgerald, President, in 1888, of the Mathematical and Physical Section of the British Association for the Advancement of Science

## Introduction

In 1861 and in 1865, Clerk Maxwell predicted theoretically that electromagnetic waves should exist in Nature and that visible light was an electromagnetic wave (the finite speed of light being, by then, well known). In 1873, in his famous *'Treatise on Electricity and Magnetism'*, Maxwell entitled one of the chapters *'On the electromagnetic theory of light'*.

At the time, there were two other theories of electricity, both rivals to Maxwell's theory. These were the theories of Wilhelm Weber and Carl Neumann and were both based on the hypothesis that electrical action *'acted directly at a distance'* whereas Maxwell's theory denied *'direct action at a distance'*. In contrast, Maxwell attributed:

> *"...electric action to tensions and pressures in an all pervading medium, these stresses being of the same kind as those familiar to engineers, with the medium being identical with that in which light is supposed to be propagated".*

Maxwell further stated in the preface to his 1873 Treatise:

> *"...it is exceedingly important that these theories be compared as they have been found to explain all electromagnetic phenomenon including the same value for the velocity of light in terms of electrical quantities...".*

## Heinrich Hertz

Up until the experiments of Heinrich Hertz, no-one had been able to make a comparison between the rival theories of electricity; but by the end of 1888, Hertz had settled the matter.

Hertz said: *"Maestro Maxwell was right. We just have these mysterious electromagnetic waves that we cannot see with the naked eye; but they are there."*

**Figure 1:** Heinrich Hertz (1857–94). Portrait by Karl Bauer, Deutsches Museum, Munich (Archive CD73408)

The hypothesis that forces manifested themselves by *'direct action at a distance'*, although a hypothesis that had troubled Sir Isaac Newton[1], was commonly held by physicists of that time. Its refutation by Hertz had wider repercussions than only in physics. His refutation contained philosophical insights into the way Nature behaved.

In a series of brilliant experiments, Heinrich Hertz (**Fig. 1**) generated electromagnetic waves in the laboratory (these waves being called *'Hertzian waves'* until about 1910). He further established that these waves travelled at a finite velocity. They obeyed the *'law of reflection'* (namely that the angle of incidence was equal to the angle of reflection) and could be refracted, polarised and blocked by objects in their path. He established that stationary waves existed and that these *Hertzian* waves had a much longer wavelength than visible light.

## Hertz and Helmholtz

In the 19th century, relations between German and British physicists were close. The German physics professor, Professor Helmholtz, had visited Lord Kelvin[2] on a number of occasions.[3] Indeed, when the *'Cavendish Professorship of Experimental Physics'* was first established at Cambridge in 1871, Professor Thomson (Lord Kelvin) had been invited to occupy the position but he was well established in Glasgow with his own busy laboratory. Professor Helmholtz had then been approached; but Helmholtz had recently been appointed to the professorship of physics at Berlin and did not wish to leave Germany. Maxwell was then approached and accepted the position.

1 See Newsletter No. 10 **https://clerkmaxwellfoundation.org/Newsletter_2018_Spring.pdf**

2 Lord Kelvin (Willian Thomson), FRS, FRSE was the Professor of Physics in Glasgow and President of the Royal Society from 1890-95 and President of the Royal Society of Edinburgh on three separate occasions.

3 On a visit to St. Andrews, courtesy of Professor Tait (Professor of Physics at Edinburgh University), Professor Helmholz had even been persuaded to try the sport of golf!

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Helmholtz had first become aware of Hertz in 1878 when the latter was a student in Berlin. The former immediately recognised in the latter a very gifted physicist who was a meticulous experimenter, par excellence, as well as being someone who fully understood the different consequences of the latest academic theories.

The *'1879 Prize Problem'* of the Prussian Academy of Sciences required *'the determination of the correctness, or otherwise, of the three rival theories of electricity'* (namely of those of Weber, Neumann and Maxwell). Helmholtz suggested, to his star pupil (Hertz), that he try to solve the *'Prize Problem'.*

However, Hertz realised that such a determination would require being able to generate electromagnetic waves of a long enough wavelength (of a matter of metres) which could be measured easily in the laboratory. If such waves were to travel at the speed of light, this would require the generation of electromagnetic waves of a frequency of around 100 million cycles per second (which we now call 100 MHz). At the time, there seemed no way of generating such high frequencies in the laboratory. Hertz therefore put the problem aside while still keeping it at the back of his mind. No-one else solved the problem and so it lapsed.

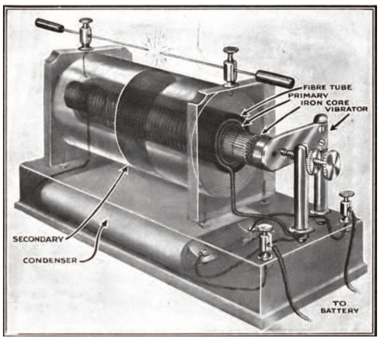


**Figure 2:** Ruhmkorff coil with its sparkgap across which sparks jumped from one metal rod to the other. Courtesy Wikipedia Commons

## Professor at Karlsruhe

By 1870s, Helmholtz had become the most important physicist in Germany. Perhaps on the strength of favourable recommendation from Helmholtz, Hertz was appointed, in 1885, a full professor of physics at Karlsruhe at the age of 28.

## Apparatus of Hertz to tackle the 'Prize Problem'

Among the laboratory equipment at Karlsruhe, Hertz found a Ruhmkorff induction coil (**Fig. 2** – called, in this article, an 'R-coil') which generated a very high alternating voltage with sparks jumping across the air-gap[4] between two pointed metal rods[5].

In order to increase the vigour of the sparks, Hertz replaced the R-coil's pointed rods with two straight wires (the two B-wires shown in **Fig. 3**) with a micrometer measuring gauge (modified to serve as an adjustable spark-gap) in the middle of the wires. This, together with the R-coil, formed the *'primary circuit'*.

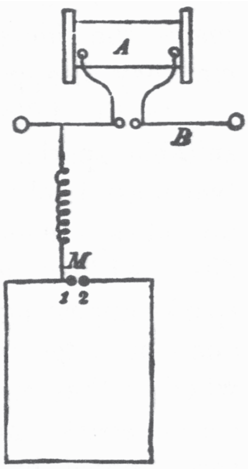


**Figure 3:** From Hertz's paper in Annalen der Physik, 31

Hertz had assumed that no sparks should remain when the R-coil's air-gap was shorted by a thick wire but he discovered, to his surprise, that, even when the spark-gap of the R-coil was shorted by a thick wire, he could not entirely eliminate the sparks. The inability to eliminate the sparks troubled Hertz and a first-class experimenter, he investigated further.

Hertz formed a *'secondary circuit'* in the form of a wire in the shape of a rectangle. This rectangular-wire formed a closed circuit apart from an air-gap which was also fitted with a micrometer gauge and with two brass knobs (shown by the letter M and marked knob 1 and knob 2 in **Fig. 3**).

The rectangular-wire was then connected to one of the two B-wires. When the R-coil was generating sparks, Hertz noticed that sparks would also be produced across the air-gap in the rectangular-wire (which we have called the *'M-gap'*).

Hertz concluded that: *"...the experiment can only be interpreted in the sense that the change in potential reaches knob 1 in an appreciably shorter time than knob 2."*

## Hertz's conclusion

The fact that Hertz had been driven to this conclusion surprised him, because, at the speed of light, changes in potential (in wires) were propagated with a velocity which was approximately the same as the known velocity of light, namely some 300,000 kilometres per second. Thus, Hertz was forced to conclude that these electrical oscillations had to have a time-period of oscillation faster than the time taken for electricity to travel round the rectangular-wire from point 1 to point 2.

Hertz estimated that this time would be of the order of $10^{-8}$ seconds (since the rectangular-wire was only some metres in length).

Hertz realised that the electrical oscillations he was generating must have a frequency of some 100 MHz. Such high oscillations had not knowingly been generated before in the laboratory. As Hertz said (at these frequencies):

*"...the direction of force alters so rapidly that the electricity has no time to distribute itself in such a way as to neutralise the effect of the force."*

4 The breakdown strength for air is about 30,000 volts per cm so high voltages are needed for sparks to appear across an air-gap.

5 We now know that electromagnetic waves arise as a result of the acceleration of electrons across the spark-gap (electrons being the very tiny negatively charged particles whose motion forms electric current). Gravitational waves arise as a result of acceleration of matter, as in the last moments of the merger of two 'black holes'.
The proof of the existence of gravitational waves (as predicted theoretically by Einstein) has been experimentally verified only in the last few years (covered in Newsletter 10 **https://clerkmaxwellfoundation.org/Newsletter_2018_Spring.pdf** ). This is a further example of Maxwell's *"...tensions and pressures..."* being passed on from one point to another at the speed of light (in this case, the curvature of space-time).

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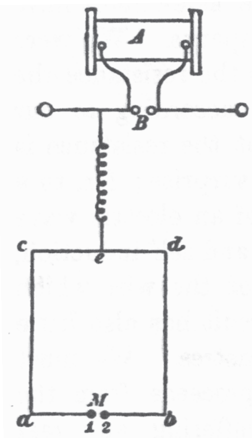

Figure 4: From Hertz's paper in Annalen der Physik, 31

## Amended Experimental Set-up

Using a slightly amended experimental set-up, Hertz progressively moved the point of connection (shown as point (e) in **Fig. 4**) between the connecting wire and the rectangular-wire.

When the connection point remained at point (e), no sparks appeared in the M-gap as both electric waves reached the M-gap at the same time. But when the connection point was moved from point (e) towards (c) or (d), sparks again appeared across the M-gap. On moving the connection point further round the rectangular-wire, the sparks ceased again. Hertz established the points on the rectangular-wire where (1) there were sparks and (2) where there were no sparks. To Hertz, this suggested that standing waves were created when the waves approaching knobs 1 and 2 (of the M-gap) met the waves reflected from knobs 1 and 2.

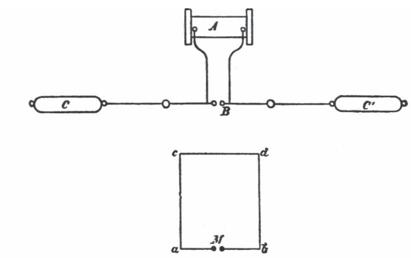

Figure 5: From Hertz's paper in Annalen der Physik 31

Hertz continued experimenting with different experimental set-ups, finding that the connecting wire between the B-wires and the rectangular-wire was not necessary (**Fig. 5**). He found that adding further capacitance (shown as C and C' in **Fig. 5**), in the form of metal plates, increased the spark length.

Hertz made two further improvements. Firstly, he realised that even more vigorous sparks could be obtained if the *primary circuit* (the *'transmitter'*) and the *secondary circuit* (the rectangular-wire *'receiver'*) were *'tuned'* to the same natural frequency of oscillation, an effect we now call *'resonance'.* Secondly, instead of the plates C and C', he used hollow zinc spheres which could be moved along the straight wire until resonance between *transmitter* and *receiver* was achieved.

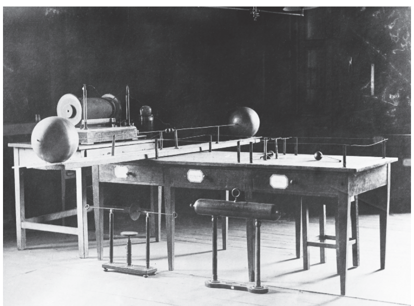
Figure 6: Original apparatus of Hertz. Deutsches Museum, Munich (Archive, DM49939)

Hertz now had the means to transmit electromagnetic oscillations into free space and receive them by means of the rectangular-wire (**Fig. 6**). He was now aware that a test of the rival theories of electricity was within his grasp.

## Experiments of Hertz

Hertz discovered that when he brought a metal probe up to the rectangular-wire (without touching it), sparks appeared in the M-gap even when the connection was in position (e). He found that sparks also appeared when a large block of insulating material (such as a solid block of pitch) was brought near to the rectangular-wire. This suggested that changes in the polarisation of insulators (Maxwell's displacement current) gave rise to electromagnetic forces no different from the forces produced by equivalent conduction currents. As this phenomenon was unique to Maxwell's theory, it counted strongly in favour of his theory.

Using a long straight wire (which we have called the *'long-wire'*, but not shown), Hertz obtained interference between the waves in the *rectangular-wire* receiver and the *long-wire*. He measured their wavelength and their speed. He obtained the result that the speed of the waves in air was in excess of the speed in wires. However, Hertz was somewhat surprised at this result because, according to theory, the speed should have been the same;[6] but, at this time, Hertz was using a small room with an iron stove in it. Nonetheless, the finding that the velocity of *Hertzian waves* was finite was of great experimental significance in Hertz's search for a true theory of the way electromagnetic waves behaved in Nature. However, when Hertz moved into a much larger room (see below), the two speeds were found to be much closer.

## A much larger room

As Hertz obtained better understanding of these *Hertzian waves,* he transported his equipment into a much larger room (a lecture theatre) to avoid his *Hertzian waves* being refected off the near walls and the iron stove of his previous room.


Figure 7: 'racquet receiver', Wikipedia Commons

Hertz also made improvements to his *receiver.* First, he coiled the wire many times and bent these coils into a circle thus making a torus. This was fixed to a frame (with a long handle like a tennis racquet) – the *'racquet-receiver'* (**Fig. 7**). The *racquet-receiver* was a closed circuit except for the spark-gap in the circumference.

6 The matter was finally settled by Sarasin and De la Rive in the early 1890s. Hertz realised that the speed would have been found to be the same had it not been that the waves bounced off the walls and stove (made of iron) in the small room he was using.

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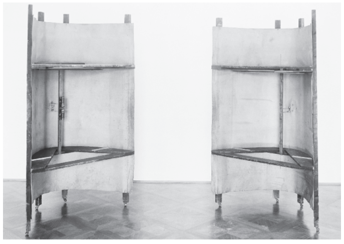

**Figure 8:** Hertz's parabolic transmitter and receiver, Deutsches Museum Munich, (Archive BN43335)

Secondly, he improved his *transmitter* to be in the form of a zinc parabola with the spark-gap situated vertically on the parabola's focal axis so that the waves propagated outward in parallel rays. The wires leading from the spark-gap were taken through holes in the zinc parabola to an R-coil situated behind the frame (**Fig. 8**).

## Much shorter waves

Hertz had discovered that the R-coil generated a particular shape of waveform which contained within it a range of frequencies, including a wave of substantially shorter wavelength than his previous wave. These much shorter waves had a frequency of some 1,000 MHz[7] and a wavelength of around some tens of centimetres. He revised the design of his *transmitter* and *receiver* to be tuned to these shorter waves.

He placed this improved *transmitter* at one end of the room with a large zinc plate at the other. Using the *racquet- receiver,* he detected the oncoming wave and the reflected wave interfering to make standing waves characterised by nodes and anti-nodes.

## Reflection and Refraction

Hertz improved his *receiver* to now consist of two vertical rods, situated one above the other, both on the optic axis of a second zinc parabola (**Fig. 8**). These rods were connected by wires which lead through the zinc parabola to the spark-gap at the back.

The improved *transmitter* and *receiver* were then placed at the same end of the lecture room. A zinc plate was attached to the wall at the opposite end of the lecture theatre.

The rays emanating from the *transmitter* were reflected off the large zinc plate and back to the *receiver*. Hertz found that the angle of incidence (of the incoming rays) had to be equal to the angle of reflection (of the outgoing rays) for sparks to appear. Hertz had shown that his *Hertzian waves* were reflected like visible light. Furthermore, a person standing in the way of the rays would block the transmission, causing the sparks in the *receiver* to cease.

Using a prism (**Figs. 9 and 10**) made of pitch, Hertz found the rays to be refracted according to Snell's law in optics.

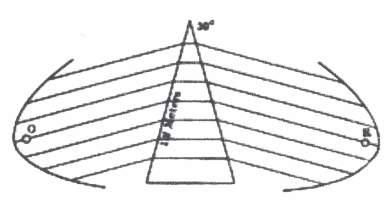


**Figure 9:** Diagrammatic representation of refraction, Wikipedia Commons

**Figure 10:** A prism used by Hertz. Deutsches Museum, Munich, (Archive, BN 43336).

7 The frequency of to-day's mobile phones is broadly around a frequency of 1,000 MHz.
8 In Fig 12, the small vertical arrow shows the direction of the electric field.

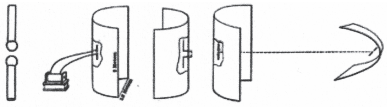

**Figure 11:** Diagrammatic representation of Polarisation, Wikipedia Commons

## Polarisation

Hertz further found that, if the axes of the parabolic *transmitter* and *receiver* were both vertical, sparks appeared but, if one axis was vertical and the other horizontal, no sparks resulted (**Fig. 11**).

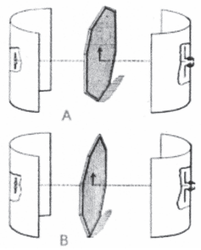


**Figure 12:** Diagrammatic representation of Hertz's frame experiment, Wikipedia Commons

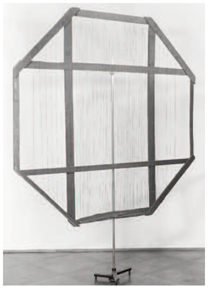

**Figure 13:** Hertz's frame for demonstrating polarisation. Deutsches Museum, Munich (Archive BN43336)

Furthermore, Hertz interposed an octagonal frame (**Figs. 12 and 13**) with parallel wires stretched across the frame[8]. When the parallel wires were vertical (as in A in **Fig. 12**) no sparks appeared but when they were horizontal (as in B in **Fig. 12**) the sparks reappeared. Furthermore, when the wires were placed at a 45° angle to the axis, sparks resumed. Thus Hertz had found that the frame was capable of resolving the incident radiation into two components, only transmitting the component perpendicular to the wires! When he had published his findings in *Annalen der Physik,* Hertz was understandably exhilarated and wrote to Helmholz:

*"The approval with which my experiments have been received has far exceeded my expectations."*

## The pleasure of Helmholtz

Helmholtz was greatly pleased to have been the first person to have been informed by Hertz about the latter's progressive successes in identifying which theory of electricity was correct. Helmholtz's faith in Hertz had been amply rewarded.

It seems to have been that, in 1888, by reading an edition of *Annalen der Physik*, Professor Lodge in England (who had himself been trying to generate electromagnetic waves in air) first realised that he had been *'scooped'* by Hertz in Germany.

Max von Laue (Nobel Prize for Physics 1914) later wrote:

*"Hertz's discovery revolutionised physics and profoundly affected the life of every individual whether he is aware of it or not."*

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*The birthplace in 1831 of James Clerk Maxwell.*

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