1 Problem

W. Lewin of MIT has given an example of a deceptively simple circuit with somewhat paradoxical behavior [1]. As sketched below, a loop containing resistors $R_1$ and $R_2$ surrounds a solenoid magnet that is excited by a time-dependent current.

This circuit is probed by two voltmeters as sketched in the righthand figure above. Each voltmeter consists of a resistor $R \gg R_1, R_2$ and an ammeter that measures the currents $I_1$ and reports the “voltage” $V_{\text{meter},i} = I_i R$. The “positive” leads of the voltmeters are connected to points $a$ and $c$, such that the directions of currents $I_1$ and $I_2$ are as shown when positive.

The paradox is that $V_{\text{meter}1}$ does not equal $V_{\text{meter}2}$, which is particularly surprising in the case that points $a$ and $c$ are the same, and points $b$ and $d$ are the same.

Discuss.

2 Solution

This problem has a long history in pedagogic lore, some of which can be traced in [7]-[24]. A position sensor base on the principle of this problem is described in [25].

2.1 Analysis via Kirchhoff’s Circuit Laws

A circuit diagram for the system is shown on the top of the next page. The solenoid magnet is the primary of a transformer that is excited by a time-dependent current $I_p$, which is assumed to be known. The loop with resistors $R_1$ and $R_2$ is the secondary of the transformer. The

https://www.youtube.com/watch?v=nQqbA2jwkWI

Another example that illustrates limitations of “ordinary” circuit analysis is the two-capacitor paradox [2].

The ambiguous meaning of “voltage” is noted, for example, in [3]. A general discussion of what AC voltmeters measure is given in [4], and the concepts of “voltage drop” and $\mathcal{E}_M\mathcal{F}$ are reviewed in [5, 6].
(small) self inductance of the secondary is $L$, and $M \gg L$ is the mutual inductance between the primary and secondary.

Kirchhoff’s circuit (loop) equation\(^4\) for the secondary loop is

\[
0 = (I + I_1)R_1 + (I - I_2)R_2 + L\dot{I} + M\dot{I}_p. \tag{1}
\]

We restrict the analysis to low frequencies such that the term $L\dot{I}$ is negligible. Since $\dot{I}_p$ is known, we define

\[
\mathcal{E} = -M\dot{I}_p = -\dot{\Phi}_p, \tag{2}
\]

where $\Phi_p$ is the magnetic flux from the primary through the secondary loop. Then, eq. (1) can be written as

\[
\mathcal{E} = (R_1 + R_2)I + R_1I_1 - R_2I_2. \tag{3}
\]

Similarly, Kirchhoff’s equations for the voltmeter loops are

\[
0 = I_1R + (I_1 + I)R_1 \approx R_1I + RI_1, \tag{4}
\]

\[
0 = I_2R + (I_2 - I)R_2 \approx -R_2I + RI_2. \tag{5}
\]

Solving the three simultaneous linear equations (3)-(5) for the currents, we find

\[
I \approx \frac{\mathcal{E}}{R_1 + R_2}, \quad I_1 \approx -\frac{\mathcal{E}R_1}{R(R_1 + R_2)}, \quad I_2 \approx \frac{\mathcal{E}R_2}{R(R_1 + R_2)}. \tag{6}
\]

The meter readings are therefore,

\[
V_{\text{meter1}} = I_1R \approx -\frac{\mathcal{E}R_1}{(R_1 + R_2)}, \quad V_{\text{meter2}} = I_2R \approx \frac{\mathcal{E}R_2}{(R_1 + R_2)}. \tag{7}
\]

which have opposite signs, and also obey $|V_{\text{meter1}}| + |V_{\text{meter2}}| = \mathcal{E}$.

\(^4\)Lewin’s has supplemented his circuit paradox with YouTube videos titled “Kirchhoff’s Loop Rule is for the Birds,” https://www.youtube.com/watch?v=LzT_YZ0xCFY, and “Is Kirchhoff’s Loop Rule for the Birds?” https://www.youtube.com/watch?v=5be3zp_j_eCY. Since Kirchhoff’s loop equation is based on conservation of energy, as reviewed in the Appendix, many of the statements in these videos are more in the nature of misdirection than explanation.
The meter readings do not depend on the locations of points \( a, b, c \) and \( d \), so long as \( a \) and \( c \) are both between resistors \( R_1 \) and \( R_2 \) on the upper wire between them, and \( b \) and \( d \) are both between resistors \( R_1 \) and \( R_2 \) on the lower wire between them, and the leads are connected in the sense of the figure below (from [17]).

These results were validated by experiment during Lewin’s lecture demonstration. However, if both meters were outside the secondary loop and their leads both attached to that loop from its “right” side as shown in the figure below, both meters would read \( \mathcal{E}R_2/R_1 + R_2 \), while if all leads were attached from the “left” side they would both read \( -\mathcal{E}R_1/R_1 + R_2 \).

2.1.1 Which Way Does Current \( I_1 \) Go Around the Secondary Loop?

In the preceding analysis we tacitly assumed that the current \( I_1 \) flows only on the left side of the secondary loop between points \( a \) and \( b \), as shown on the left below. But it could be that the current flowed on the right side of the secondary loop, as shown
on the right above. In this case Kirchhoff’s law for the secondary loop is

\[ E = IR_1 + (I - I_1)R_2 = (R_1 + R_2)I - R_2I_1, \]  

(8)

while Kirchhoff’s law for the voltmeter loop is

\[ -E = I_1R + (I_1 - I)R_2 \approx -R_2I + RI_1, \]  

(9)

noting that now all the magnetic flux in the solenoid is linked by the voltmeter loop, but since the sense of current \( I_1 \) is defined to be opposite to that of current \( I \) the effective EMF in the voltmeter loop is \(-E\) rather than \(E\). Solving eqs. (8)-(9) for the currents we find

\[ I = \frac{E}{R_1 + R_2}, \quad I_1 = -\frac{ER_1}{R(R_1 + R_2)}, \]  

(10)

as found in eq. (6) assuming that current \( I_1 \) flowed on the left side of the secondary loop. Hence, the value of the current \( I_1 \) does not depend on whether it flowed on the left or on the right side of the primary loop, and the circuit analysis based on Kirchhoff’s law cannot determine the partitioning of current \( I_1 \) between the left and right sides.

However, the amount of heat dissipated in resistors \( R_1 \) and \( R_2 \) depends on the partitioning of current \( I_1 \) between them. We suppose that the partition minimizes the heat dissipation.\(^5\) Defining \( f \) to be the fraction of current \( I_1 \) that passes through resistor \( R_1 \), the power dissipated in the two resistors is

\[ P = (I + fI_1)^2R_1 + [I - (1 - f)I_1]^2R_2 = 2fII_1(R_1 - R_2) + f^2I_1^2(R_1 + R_2) + \text{constant}. \]  

(11)

On minimizing the power \( P \) we find that

\[ f = -\frac{I}{I_1} = \frac{R}{R_1} \gg 1. \]  

(12)

Since \( f \) cannot be larger than 1, we infer that \( f = 1 \), and all the current \( I_1 \) flows through resistor \( R_1 \) as initially assumed.

2.1.2 The Voltmeter Leads Pass Through the Interior of the Secondary Loop

Suppose the voltmeter leads cross the interior of the secondary loop, such that a fraction \( f \) of the magnetic flux of the solenoid passes through the voltmeter loop, as shown in the sketches below.

\(^5\)Here, we follow Heaviside, p. 303 of [26].
As discussed in sec. 2.1.1, it suffices to suppose that all of current $I_1$ passes through resistor $R_1$. Then, Kirchhoff’s law for the secondary loop is

$$\mathcal{E} = (I + I_1)R_1 + IR_2 = (R_1 + R_2)I + R_1I_1,$$

while Kirchhoff’s law for the voltmeter loop is

$$f\mathcal{E} = I_1R + (I_1 + I)R_1 \approx R_1I + RI_1,$$

noting that the sense of current $I_1$ is the same as that of current $I$, such that the $\mathcal{EMF}$ which drives the voltmeter loop is $f\mathcal{E}$. Solving eqs. (13)-(14) for the currents we find

$$I = \frac{\mathcal{E}}{R_1 + R_2}, \quad I_1 = -\frac{\mathcal{E}[R_1 - f(R_1 + R_2)]}{R(R_1 + R_2)}.$$  

(15)

The limiting cases for the current $I_1$ are

$$I_1(f = 0) = -\frac{\mathcal{E}R_1}{R(R_1 + R_2)}, \quad I_1(f = 1) = \frac{\mathcal{E}R_2}{R(R_1 + R_2)},$$  

(16)

which correspond to the previous results for the voltmeter on the “left” and on the “right”, respectively. Thus, there is a continuum of possible readings of the voltmeter between the “left” and “right” readings, depending on the routing of the voltmeter leads.

### 2.2 Scalar and Vector Potentials

The fact that the two meters give different readings when $a = c$ and $b = d$ (in sec. 2.1) indicates that the meter readings are not simply related to the electric scalar potential $\mathcal{V}$ at those points, as would be the case for a DC circuit.

In DC circuit analysis, ideal conductors (such as we have tacitly assume all wires in the system to be) are equipotentials. However, in time-dependent circuit analysis the proper assumption is that the electric field tangential to the wires is zero (in the limit of perfectly conducting wires).

In time-dependent situations the electric field $\mathbf{E}$ is related to both the scalar potentials $\mathcal{V}$ as well as to the vector potential $\mathbf{A}$ according to

$$\mathbf{E} = -\nabla \mathcal{V} - \frac{\partial \mathbf{A}}{\partial t}.$$  

(17)

Supposing that the secondary loop is circular, its tangential component $E_\phi$ is given

$$E_\phi = -\frac{1}{r} \frac{\partial \mathcal{V}}{\partial \phi} - \frac{\partial A_\phi}{\partial t}.$$  

(18)

Since $\mathbf{B} = \nabla \times \mathbf{A}$, we have from Stoke’s theorem that $\oint \mathbf{A} \cdot d\mathbf{l} = \int \mathbf{B} \cdot d\text{Area} = \Phi$, so the azimuthal component $A_\phi$ if the vector potential is given by

$$A_\phi = \frac{\Phi}{2\pi r},$$  

(19)
where \( r \) is the radius of the secondary loop. In the present example the magnetic flux \( \Phi \) through the secondary loop has contributions from the magnetic fields due to all four currents \( I_p, I, I_1 \) and \( I_2 \). Of these only the contribution \( \Phi_p \) from the primary current \( I_p \) is significant.

Applying this to wire segments in the central loop, for which \( E_\phi = 0 \), we have that

\[
\frac{\partial V}{\partial \phi} = -r \frac{\partial A_\phi}{\partial t} = -\frac{\dot{\Phi}}{2\pi} \approx -\frac{\dot{\Phi}_p}{2\pi} = \frac{E}{2\pi},
\]

recalling eq. (2), and so the scalar potential along a wire segment has the form

\[
V(\phi) = V_0 + \frac{E\phi}{2\pi}, (21)
\]

where \( \phi \) increases for counterclockwise movement around the loop.

The voltage drops\(^6\) across resistors \( R_1 \) and \( R_2 \) are

\[
\Delta V_1 \approx IR_1 \approx \frac{E R_1}{(R_1 + R_2)}, \quad \Delta V_2 \approx IR_2 \approx \frac{E R_2}{(R_1 + R_2)}, (22)
\]

if the azimuthal extent of the resistors is negligible, and we now move in a clockwise sense around the loop. In this convention the voltage drop along each of the wire segments of the secondary loop are \(-E/2\), so the total voltage drop around the loop is zero, as expected for the scalar potential. Finally, the voltage drops between the points where the voltmeters are attached to the central loop are

\[
V_a - V_b \approx \frac{E \phi_1}{2\pi} - \frac{E R_1}{(R_1 + R_2)}, \quad V_c - V_d \approx -\frac{E \phi_2}{2\pi} + \frac{E R_2}{(R_1 + R_2)}.
\]  

Only if the meter leads were connected directly to the ends of resistors \( R_1 \) and \( R_2 \) (as would be good practice) would the meter readings equal the voltage differences (differences in the electric scalar potential) between the tips of the leads.\(^7\)

For additional examples of the relation of voltmeter readings to the scalar and vector potentials in time-varying situations, see [4].

\(^6\)In this note we use the term voltage drop to mean the difference in the electric scalar potential \( V \) between two points. Calling those points \( a \) and \( b \), the voltage drop between them is \( \Delta V = V_a - V_b \). In Lewin’s example, a meter reading, \( V_{\text{meter}} \), does not equal the voltage drop between the tips of its leads.

\(^7\)If the meter leads cross the region of magnetic flux from the solenoid, intercepting fraction \( f \) of that flux as in sec. 2.1.2, there is always a set of points \( \{a, b\} \) such that the meter reading equals \( V_a - V_b \). In particular, if \( f = 1/2 \) the desired points are halfway between the two resistors, as noted in [16]. However, in these cases the meter leads cannot be short.
2.2.1 Secondary Loop of Resistive Wire

In an early statement [10] of the present problem, resistors 1 and 2 were not localized objects. Rather, the secondary loop was made of a resistive wire of total resistance $R_0$. Then, the current $I$ in the loop would be $\mathcal{E}/R_0$. In this case, the $IR$ drop between points $a$ and $b$ that subtend angle $\phi$ is $IR_0\phi/2\pi = \mathcal{E}\phi/2\pi = V_a - V_b$. That is, in this version the $IR$ drop equals the difference in the scalar potential between two points, which is perhaps less instructive than the case with localized resistors.

2.2.2 On the “Reality” of the Vector Potential

The example of a long solenoid (or toroid) with “zero” magnetic field, but nonzero vector potential, outside the coil, is often used to argue that the vector potential (or at least differences in the vector potential) should be considered as “real” (i.e., having measurable effect). The best known of the arguments in the quantum example of Aharonov and Bohm [27], although this independently restates an earlier argument by Ehrenberg and Siday [28]. A related argument for classical electrodynamics has been given by Konopinski [29]; see also [30, 31].

The classical argument is weaker, being that the electric field outside the solenoid with a time-varying current is due to the magnetic field inside the solenoid according to Faraday’s law, but the magnetic field is “zero” outside the solenoid, so this effect appears to be action at a distance. Since field theory was developed with the goal of eliminating action at a distance, it seems that the “local” result,

$$E_{\text{induced}} = -\frac{\partial A}{\partial t},$$

implies that we should consider the vector potential to be “real”. However, as noted by Lodge in 1889 [7], the magnetic field outside the solenoid is not strictly zero, and we can argue that the weak time-varying magnetic field outside the solenoid “creates” the induced electric field there.\(^8\)

The quantum argument seems stronger, in that even for a static magnetic field in the solenoid, there is a detectable effect on the trajectories of electrons that pass outside the solenoid [27, 28]. Independent of the skepticism expressed in articles such as [34], the author notes that the supposedly “real” vector potential in the examples of Lewin, and of Aharonov and Bohm, is the gauge-invariant rotational part of the vector potential,\(^9\) which is the total vector potential in the Coulomb gauge. This vector potential includes terms that depend on the instantaneous current distribution throughout the Universe, i.e., it incorporates action at a distance. The author’s attitude is that any quantity which involves action at a distance is not physically “real”,\(^10\) and hence even the gauge-invariant part of the vector potential should not be regarded as “real”.\(^11\)

\(^8\)In greater detail, weak radiation fields exist outside a time-varying solenoid (and toroid), which must be considered in a full classical description. See, for example, [30, 32, 33].

\(^9\)See, for example, sec. 2.1 of [35].

\(^10\)The wave function of nonrelativistic quantum mechanics is such a quantity, and thus not “real” in the author’s view.

\(^11\)The Aharonov-Bohm effect involves action at a distance in terms of the vector potential as well as the fields if one uses the Poincaré gauge [36].
2.3 Comments

Suppose a voltmeter were connected to two points on the upper wire between resistors 1 and 2, as shown in the sketch below. The voltmeter loop is not coupled to the solenoid, so there is no (or extremely little) EMF induced in this loop, and hence \( I_1 = 0 \), and the meter reading would be \( V_{\text{meter}} = 0 \).

However, the difference between the scalar potential at points a and b is

\[
V_a - V_b \approx \frac{\mathcal{E} \phi}{2\pi},
\]

where \( \phi \) is the azimuthal angle between the two points, recalling CEQ. (21). While the meter does not read the difference in the scalar potential between the tips of its leads, the result \( V_{\text{meter}} = 0 \) is appealing in that we might na"ively expect the “voltage drop” to be zero between points along a good/perfect conductor.

This leads some people to argue that the term “voltage drop” should not be defined as the (unique) difference in the scalar potential \( V \) between two points (as done in this note), but rather this term should have only the operational meaning as the value measured by a voltmeter when connected to those two points. While possibly appealing in examples such as the present, this usage renders the concept of “voltage drop” to be more a property of the voltmeter (and the routing of its leads) than of the circuit it probes. See [4] for further discussion.

In the present example,

\[
V_{\text{meter}} = \int_a^b \mathbf{E} \cdot d\mathbf{l}_{\text{leads}} = -\int_a^b \mathbf{E} \cdot d\mathbf{l}_{\text{loop containing } R_1 \text{ and } R_2}. \tag{26}
\]

While some people designate the integral \( \int_a^b \mathbf{E} \cdot d\mathbf{l} \) as a “voltage drop,” we advocate calling this the \( \mathcal{E} \mathcal{M} \mathcal{F} \) between points a and b, and that the “voltage drop” between points a and b be reserved to mean simply \( V_a - V_b \), the difference in the scalar potential between the two points [37].
A Appendix: Kirchhoff’s Circuit Laws

In 1845, Kirchhoff (age 21) gave his circuit laws [38, 39] for a network of batteries and resistors, as a generalization of Ohm’s law (1827) [40] that a circuit consisting of a battery with electromotive force $E$ and electrical resistance $R$ supports and electric current $I$ related by $E = IR$. For example, in a circuit consisting of a single loop with several batteries and several resistors, the circuit (loop) equation is $\sum E = I \sum R$.

Kirchhoff never applied his laws to time-dependent circuits, such as in Lewin’s example.\(^{12}\)

A.1 Helmholtz

An early, important development of DC circuit theory was made by Helmholtz in 1853 [57], when he discussed what is now called Thévinin’s theorem [58], that any complicated but “linear” circuit is equivalent to a single source of electromotive force and a single resistance

\[^{12}\text{In 1857, Kirchhoff published two papers [41, 42] on the motion of electricity in wires, based on Weber’s (action-at-a-distance) electrodynamics [43]. The consideration of a single wire by Kirchhoff followed the practice of telegraphy at the time [44]-[48], in which only a single wire appeared to be involved, and the role of the “ground”/“earth” as a return path to “complete the circuit” was not yet recognized, as were neither the capacitance between the wire and “ground” nor the self inductance of the wire + “ground” circuit. The kind of derivation of the “telegrapher’s equation” for a two-wire telegraph “line” found in textbooks today, using Kirchhoff’s circuit laws, was first given by Heaviside in 1876 [49]. See also the Appendix of [50].}
\]

Weber followed Neumann (1845) [51] who had introduced the concepts of self and mutual inductance or circuits, $L$ and $M$, as well as the vector potential $A$. For example, the magnetic flux $\Phi$ through circuit 1 due to current $I_2$ in circuit 2 is related by $\Phi_{12} = M_{12}\cdot I_2 = \oint B_2 \cdot d\text{Area}_1 = \oint A_2 \cdot d\text{l}_1$. We would add that the integral form of Faraday’s law then tells us that if current $I_2$ varies with time, a (vector) $\mathcal{EMF}$ is induced in circuit 1 related by $\mathcal{E}_{12} = -\Phi_{12} = -M_{12}\cdot I_2$. However, Neumann, Weber and Kirchhoff did not say this, but rather emphasized the (vector) electromotive force (elektromotorische Kraft) of one current element on another, writing the magnitude of the (electromotive) force on current element 1 due to changes in current element 2 as $\mathcal{E}_{12} = k_{12}\cdot I_2$, where $k_{12}$ is a geometric factor.

Rather impressively, Kirchhoff [41] considered the (scalar) $\mathcal{EMF}$ of one current element of a single wire on another current element thereof to deduce a wave equation for the current and charge on that wire, with the wavespeed given by $c = 1/\sqrt{\mu_0/\epsilon_0}$, where the constants $\epsilon_0$ and $\mu_0$ can be determined from electro- and magnetostatic experiments (Weber and Kohlsrausch (1856) [52]), and the value of $c$ was close to the speed of light as then known. However, as Weber’s electrodynamics was based on action-at-a-distance, and was not a field theory in the sense of Faraday, Weber and Kirchhoff did not infer that, since electric waves on wire moved at light speed, light must be an electromagnetic phenomenon.

In retrospect, we might say that while Kirchhoff had an inadequate model of the capacitance $C$ and inductance $L$ per unit length along a transmission line, he obtained a valid wave equation because of a general (geometrical) result that $LC = \epsilon_0\mu_0 = 1/c^2$ for a one-dimensional transmission line, if dielectric effects can be ignored, and the current flows only on the surface of the conductors. Kirchhoff more-or-less proved this without realizing it. See, for example, pp. 255-256 of [53] and pp. 155-157 of [54]. This result does not hold a (two-dimensional) wire loop, so Kirchhoff’s consideration of this case in [41] is doubtful.

In [41], Kirchhoff discussed waves on a straight wire, and a circular wire loop of circumference $= n\lambda$ (which now finds application as a self-resonant loop antenna, particularly for $n = 1$). An ingredient in his analysis was that the electromagnetic potentials $V$ and $A$ were subject to the condition $\nabla \cdot A = (1/c)\partial V/\partial t$ (in Gaussian units), now known as the Kirchhoff gauge [55], the first-ever use of a gauge condition. In Maxwell’s theory and in the Kirchhoff gauge, the potential $V$ can be said to propagate with imaginary velocity, $ic$ [55].

Kirchhoff also gave an analysis [42] for straight wires similar to that of Thomson [56], that the potential (and electric charge density) on a wire of length $l$ with resistance $R$ and capacitance $C$ obeys the diffusion equation $d^2V/dx^2 = (RC/l^2)dV/dx$ (which does not involve the constant $c$), when effects of self inductance are ignored.
(or impedance in case of time-dependent circuits,\textsuperscript{13} which were not considered by either Helmholtz or Thévinin).\textsuperscript{14}

Joule (1841) \[61\] had established that a current $I$ through a resistor $R$ generates heat at the rate $I^2R$ whether or not $I$ is constant, as an example of conservation of energy.\textsuperscript{15}

Perhaps the first quantitative study of time-dependent electrical circuits was reported by Weber in 1846, sec. 14 of [43], who measured the characteristic time of the discharge of a capacitor (Leyden jar) through a resistor, without offering any theoretical analysis of this phenomenon.

In 1847, Helmholtz, p. 43 of [63], p. 142 of [64], considered the heat generated by the discharge of a capacitor $C$ and argued that the initial (potential) energy of the capacitor was $Q^2/2C$, where $Q$ is the charge on one if its electrodes. He also considered the effect of a moving magnet on an electrical circuit, p. 64 of [63], p. 158 of [64], using conservation of energy to deduce a circuit equation, although this is for a phenomenon beyond the scope of Kirchhoff’s laws (which apply to circuits “at rest”). Helmholtz did not consider the case of a circuit with self induction at this time.

In 1850, Helmholtz studied the propagation of electrical signals in nerves, modeling this as a resistor and a coil/inductor. When a sharp rise in electric potential was applied to this circuit, the current took a characteristic time to approach its asymptotic value. Helmholtz reported experimental results in [65, 66], and gave perhaps the first-ever time-dependent circuit analysis in [67]. He did not derive a circuit equation, but simply stated a hypothesis (Voraussetzung), p. 510 of [67], to be confirmed (or not) by experiment, that Ohm’s law would be modified by the presence of the coil to read, Helmholtz’ eqs. (2)-(3),

$$IR = E - L \frac{dI}{dt}, \quad I = \frac{E}{R} \left(1 - e^{-Rt/L}\right),$$

where $I$ is the current, which is zero at time $t = 0$ when electromotive force $E$ is applied to the circuit that has resistance $R$ and self-inductance $L$.\textsuperscript{16} The data agreed well with this model, which can be said to provide the first extension of Ohm’s law/Kirchhoff’s loop equation to a time-dependent circuit.

\textbf{A.2 Thomson}

In 1848-1853, W. Thomson \[68, 69, 70, 71, 72\] addressed Weber’s experiments [43] on the discharge of a capacitor through a resistor, advocating consideration of conservation of energy.

Thomson argued [71], following remarks by Faraday [73], that if the circuit carries current $I$ it is also associated with a kind of “kinetic” energy equal to $LI^2/2$, where $L$ is the self inductance of the circuit. Then, as the capacitor discharges, its (potential) energy is

\begin{footnotesize}
\textsuperscript{13}The term \textit{impedance} was introduced by Heaviside in 1886 [59].
\textsuperscript{14}For historical comments on Helmholtz, Thévinin and others, see [60].
\textsuperscript{15}This followed the much earlier demonstration of the mechanical equivalent of heat by Rumford [62].
\textsuperscript{16}Helmholtz called the self inductance the \textit{Potential} $P$, following Neumann [51], who invented the notion of self inductance, and apparently was consulted by Helmholtz during these studies. Helmholtz may have been the first to state that a changing current in a loop generates an $\mathcal{E}\mathcal{M}\mathcal{F}$ given by $-L\dot{I}$, although this result was implicit in Neumann’s work [51].
\end{footnotesize}
transformed into “kinetic” energy plus heat, according to eq. (2) of [71],

\[ -\frac{d}{dt} \frac{Q^2}{2C} = \frac{d}{dt} \frac{LI^2}{2} + I^2R, \quad I = \frac{dQ}{dt}, \quad 0 = LI + IR + \frac{Q}{C}. \]  

(28)

Thomson noted that if the self inductance is negligible, the circuit equation becomes

\[ I = \frac{dQ}{dt} = -RC, \quad I = I_0 e^{-t/RC}, \]  

(29)

while in general the current exhibits a damped oscillation, with frequency approximately \(1/\sqrt{LC}\) for small \(R\).

A.3 Maxwell

Thomson did not consider the case of an \(R-L-C\) circuit with an impressed \(\mathcal{E}_M\mathcal{F}\) (such as a battery or electric generator), which may have first been done by Maxwell in 1868 [74]. Maxwell actually analyzed a coupled \(R-L-C\) circuit, shown below,\(^{17}\) which was driven by the generator on the left, while \(P\) labels the potential difference \(Q/C\) across the capacitor, and \(p\) is a resistor (not an inductor).

Maxwell simply stated without justification that the circuit equations are

\[ P = \frac{Q}{C} = I_yR_p, \quad C\frac{dP}{dt} = \frac{dQ}{dt} = I_x - I_y, \quad -\mathcal{E} + I_xR + L\frac{dI_x}{dt} + \frac{Q}{C} = 0, \]  

(30)

where our \(-\mathcal{E}\) is Maxwell’s \(Mn \cos nt\), the electromotive force of the electromechanical generator. The third of eq. (30) is Kirchhoff’s loop equation as we know it today, for the left loop of the above circuit. Since Maxwell was a disciple of Thomson, we infer that Maxwell deduced the loop equation following Thomson’s energy method.

Maxwell discussed Kirchhoff’s relations for circuits with only batteries and resistors in Art. 282 of his Treatise (1873) [75]. He considered an \(R-C\) circuit (with no battery) in Art. 355, noting that both of these circuit elements have the same electric potential difference \(V\) across them,

\[ V = \frac{Q}{C} = IR, \quad I = -\frac{dQ}{dt}, \quad \frac{dQ}{dt} = -\frac{1}{RC}, \quad Q = Q_0 e^{-t/RC} \quad \text{(Maxwell)}. \]  

\(^{17}\)This may be the first figure in which circuit elements were depicted (somewhat) abstractly, rather than realistically. At this time, leading French artists were moving from realism to impressionism.
where $Q$ is the charge on one of the electrodes of the capacitor and $I$ is the current through the resistor. Maxwell’s analysis of Art. 355 was not quite the same as would follow from a generalization of Kirchhoff’s loop equation to include a capacitor, as that would read

$$0 = IR + \frac{Q}{C}, \quad I = \frac{dQ}{dt}, \quad \frac{dQ}{dt} = -\frac{Q}{RC}, \quad Q = Q_0 e^{-t/RC} \quad (\text{Kirchhoff}). \quad (32)$$

While the final result is the same, the logic of the two analyses is somewhat different.

Maxwell considered $R-L$ circuits via a Lagrangian (energy) method in Arts. 578-583 of [76] (which suggests that he had also used this method in [74]). This has the advantage of clarifying how the changes in energy associated with the mutual inductances between multiple circuits appear in the various loop equations. Maxwell did not include capacitance in his Lagrangian analysis, but simply added the capacitative $\mathcal{E}\mathcal{M}\mathcal{F}$, $Q/C$, to the circuit equations in specific examples, including $R-L-C$ circuits in Arts. 778-779, and an $R-C$ circuit in Art. 780 (where the analysis was as in our eq. (32)).

Thus, Kirchhoff’s laws for $R-L-C$ circuits as still used today appeared in Maxwell’s Treatise, although not identified there with Kirchhoff.

### A.4 Applicability of Kirchhoff’s Loop Equations

The energy methods of Helmholtz, Thomson and Maxwell clarify that the terms in Kirchhoff’s loop equations are $\mathcal{E}\mathcal{M}\mathcal{F}$’s, and not necessarily “voltages.”

It is common practice to associate the terms of the loop equations with “circuit elements,” such as batteries, generators, resistors, capacitors and inductors. While use of Kirchhoff’s laws permits computation of the currents, identifying where the associated $\mathcal{E}\mathcal{M}\mathcal{F}$’s are located is not always crisp, and interpreting measurements of currents by “voltmeters” can lead to misinterpretations of the results if one supposes that “voltmeters” measure “voltages.”

This issue is particularly acute if some loops have magnetic flux that is not contained in a small coil of the “wire” of that loop. In Lewin’s example, the magnetic flux in the primary solenoid may well be within a small coil, but the secondary consists of only a single “turn,” so the associated inductive $\mathcal{E}\mathcal{M}\mathcal{F}$ is not well localized, but rather is distributed around the entire secondary loop. Then, since inductive $\mathcal{E}\mathcal{M}\mathcal{F}$’s are associated with a vector potential, rather than a scalar potential, it can be misleading to interpret the inductive $\mathcal{E}\mathcal{M}\mathcal{F}$ as related to a “voltage.”

As Kirchhoff’s loop equation including capacitors and inductors is deduced from considerations of energy conservation, it has rather general application.

However, if the circuit involves energy in other forms than Joule heating, and the “potential” and “kinetic” energies stored in the capacitors and inductors, one must proceed with care. An important case of this type is a circuit (antenna) that emits radiation which travels away from the circuit (called the “waste” by Heaviside [77]).

A tacit assumption of Kirchhoff’s equation is that the current is the same in all elements of the circuit if it consists of only a single loop. This is not the case at very high frequencies, where the wavelength is smaller than the size of the circuit.

Even in these cases one can make a Thévenin equivalent analysis with respect to two terminals, so long as their spacing is small compared to a wavelength. Then, the circuit
can still be described as having an effective impedance, which permits use of Kirchhoff’s laws. Of course, computation of the effective impedance requires techniques beyond those of Kirchhoff.

Lewin’s circuit is within the range of applicability of Kirchhoff’s loop equations, which can be used to predict measurements by the “voltmeters” in the experiment. However, this experiment highlights the fact that “voltmeters” actually measure the current inside them, and interpreting their measurements as being proportional to the “voltage drop” along a segment of the test circuit is not valid, in general.

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