CHAPTER

22

Electrical Analogs for Water Movement through the Soil–Plant–Atmosphere Continuum

In the Preface, we noted that this book follows water as it moves through the soil–plant–atmosphere continuum (SPAC). John R. Philip pioneered the concept of the SPAC for water transfer. (See the Appendix of Chapter 13 for a biography of Philip.) He defined the SPAC as follows (Philip, 1966, p. 246): "Because water is generally free to move across the plant–soil, soil–atmosphere, and plant–atmosphere interfaces it is necessary and desirable to view the water transfer system in the three domains of soil, plant, and atmosphere as a whole. Under some circumstances, and for some purposes, we can, of course, isolate certain parts of the total system and study only certain modes of water transfer; but a general appreciation of the plant water relations of the whole plant in nature must involve the soil–plant–atmosphere continuum (SPAC)". In an earlier paper, Philip (1957) discusses the SPAC and diagrams it (Figure 22.1), but he does not use the abbreviation SPAC.

Philip (1966, p. 257) credits Gradmann (1928) for providing the initial steps toward the formulation of the SPAC. Gradmann recognized the existence of systematic gradients of potential in the plant and atmosphere, with continuity of potential at the interface. Gradmann's Figure 1 (1928, p. 3; reproduced here as Figure 22.2) represents the "Schema des Saugkraftabfalles" ("Diagram of the Decrease in Suction Force"), and it has three lines: AB, BC, and CD. Line CD shows the fall in suction force between the air and the surface of the plant; line BC shows the fall from the outside surface of the plant to the plant; and line AB shows the fall from the plant to the soil. The total drop goes from 1000 atm (in the air) to 0 atm (in the soil). Gradmann's insight was neglected by other workers for nearly

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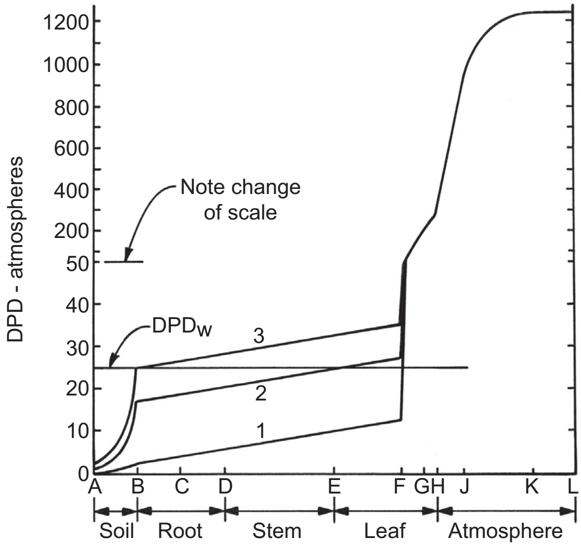

FIGURE 22.1 The soil-plant-atmosphere continuum, showing energy profiles, (1) during normal transpiration; (2) during temporary wilting; (3), at permanent wilting. DPD = diffusion pressure deficit. Points on the transpiration path: A. Soil (a definite distance from plant root); B. Surface of root hairs and of absorbing epidermal cells; C. Cortex; D. Endodermis; DE. Vessels and tracheids in the xylem; E. Leaf veins; F. Mesophyll cells; FG. Intercellular space and substomatal cavity; GH. Stomatal pore; HJ. Laminar sublayer; JK. Turbulent boundary layer; KL. Free atmosphere. *Redrawn from Philip (1957). From Kirkham (2002, Figure 1, p. 328). Reproduced by permission of the American Geophysical Union, CSIRO Publishing, and John Wiley and Sons.*

20 years, when van den Honert (1948) drew attention to it in the English literature (Kirkham, 2002). Later, in this chapter, we shall return to van den Honert's analysis.

Electrical analogs have long been used to study the movement of water in soil. The analogy between the flow of electricity through conducting media and the flow of water through porous media (i.e., soil) was pointed out by Slichter (1899), a mathematician at the University of Wisconsin. The analogy was later expanded to include the movement of water through the entire SPAC. We now consider why the analogy works and its application.

22.1 THE ANALOGY

The analogy can be seen when we compare Ohm's law with Darcy's law. Ohm's law states (Kirkham and Powers, 1972, p. 183) that

$$I = -\sigma A(V_2 - V_1)/L = V/R, \tag{22.1}$$

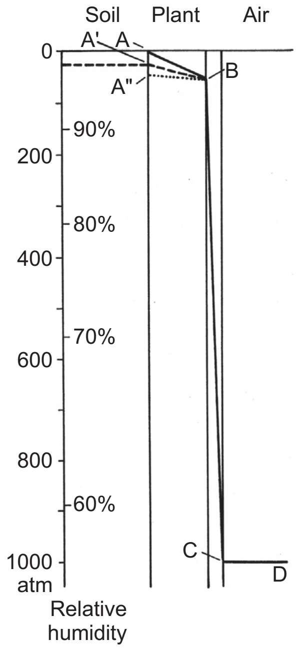

FIGURE 22.2 Diagram of the decrease in suction force. *Redrawn from Gradmann, 1928; translated into English; original German words at the top were Boden, Pflanze, Luft, and the "relative humidity" at the bottom was abbreviation R.F. by Gradmann. From Kirkham (2002, Figure 2, p. 328). Reproduced by permission of the American Geophysical Union, CSIRO Publishing, and John Wiley and Sons.*

where

I = quantity of electricity flowing per unit time (coulombs of electricity per unit time) (coulombs per second or amperes),
σ = specific electrical conductivity or electrical conductivity (Siemens per centimeter),
L = length of the element through which current flows (centimeters),
A = cross-sectional area of the element (square centimeter),
V_2 and V_1 = voltages (volts),
$(V_2 - V_1)/L$ = potential gradient,
R = resistance (ohms).

For water flow in porous media (Darcy's law), we can write (Kirkham and Powers, 1972, p. 183)

$$Q = -KA(\phi_2 - \phi_1)/L, \tag{22.2}$$

where

Q = cubic centimeter of water flowing per unit time (cubic centimeter per second),
K = hydraulic conductivity (centimeter per second),
L = length (centimeter),
A = cross-sectional area (square centimeter),
φ_2 and φ_1 = hydraulic heads (centimeter),
$(\varphi_2 - \varphi_1)/L$ = hydraulic gradient.

We immediately see the close analogy between Ohm's law (Eqn (22.1)) and Darcy's law (Eqn (22.2)). (For a biography of Ohm, see the Appendix, Section 22.8.)

22.2 MEASUREMENT OF RESISTANCE WITH THE WHEATSTONE BRIDGE

To measure R (resistance in ohms; the Greek letter capital omega, Ω, is used to symbolize resistance in ohms), we use a Wheatstone bridge, which is an instrument for measuring the value of an unknown resistance by comparing it with a standard. This method, devised in 1833 by S. Hunter Christie, was brought to public attention by the English physicist, Sir Charles Wheatstone (1802–1875) and has remained associated with his name (Hausmann and Slack, 1948, p. 388). (For a biography of Wheatstone, see the Appendix, Section 22.9.) The Wheatstone bridge is the most convenient, and at the same time accurate, way of measuring resistances of widely different values (Ingersoll et al., 1953). It works on the principle of a divided circuit, which is illustrated in Figure 22.3. The current from the battery divides between the two branches abc and adc. Because the potential drop is the same along the two branches, corresponding

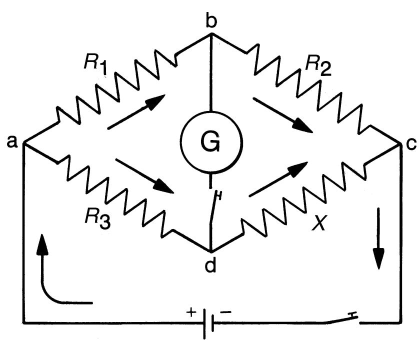

FIGURE 22.3 Wheatstone bridge circuit. *From Ingersoll et al. (1953, p. 134). This material is reproduced with permission of The McGraw-Hill Companies.*

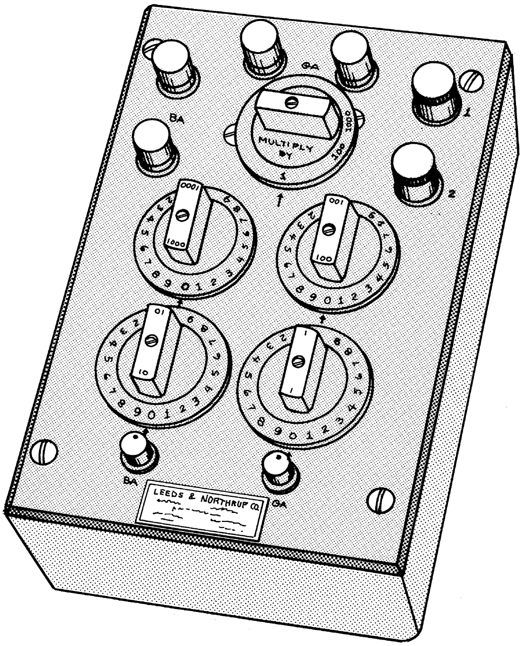

FIGURE 22.4 A Wheatstone bridge. *From a brochure of Leeds and Northrup Co., North Wales, Pennsylvania. Courtesy of Honeywell International, Inc.*

intermediate points b and d may be found that are at the same potential. Under these circumstances, no current will flow through the galvanometer, G, connected between b and d. The bridge is then said to be balanced, and

$$R_1/R_2 = R_3/X. \tag{22.3}$$

Thus, any one of the four resistances may be obtained in terms of the three others.

A Wheatstone bridge often looks like a black box with knobs on the top (Figure 22.4), but there are also "slide-wire" Wheatstone bridges. In the slide-wire form of the bridge, one of the branches (e.g., abc in Figure 22.3), consists of a wire of uniform cross-section. The point b is located by a sliding contact. The unknown resistance X is placed in one arm of the other branch, the remaining arm containing the known resistance R_3 usually in the form of a resistance box. Because only the ratio of the resistances R_1 and R_2 is required, this ratio may be replaced by the ratio of the lengths of the two arms of the slide wire (Ingersoll et al., 1953, p. 135).

22.3 LAW OF RESISTANCE

We know R, by measuring it with the Wheatstone bridge, but now, we need to know conductivity. To determine conductivity, we use the law of resistance. The law of resistance is true by experimentation, and states that

$$R = \rho L/A, \tag{22.4}$$

where

R = resistance (ohms),
L = length (centimeter),
A = area (square centimeter),
ρ = resistivity (ohms centimeter).

Figure 22.5 illustrates how we can apply the law of resistance. If we have a cube of material that is 1 cm on a side for a total cross-sectional area of 1 cm^2 and a length of 1 cm through which the electricity flows, and we have a 1-V potential difference in our circuit and we have 1 ampere of electricity flowing (I) (1 ampere = 1 coulom b/s or 1 A = 1 C/s), we have 1 Ω of resistance, because by Ohm's law R (ohms) = V (volts)/ I (amperes). We know R, L, A, and we can determine resistivity from the law of resistance. From resistivity, we determine conductivity, as follows:

$$\sigma = \text{conductivity} = 1/\text{resistivity} = 1/\rho.$$

The units of conductivity = 1/(ohms centimeter) or mhos per centimeter. (These are not SI units; we will change these to SI units in the next section.)

Resistivity (ρ) varies with materials. The resistivity of materials can be found in an early edition of the *Handbook of Chemistry and Physics* (Hodgman, 1959, p. 2598). The resistivity of rocks and soils is high. For example, the resistivity of granite varies between 10^7 to 10^9 Ω-cm, and the resistivity of sand varies between 10^5 to 10^6 Ω-cm. (The temperature at which the resistivity of rocks and soils was determined is not stated in the handbook.) The resistivity of metals is small (Hodgman, 1959,

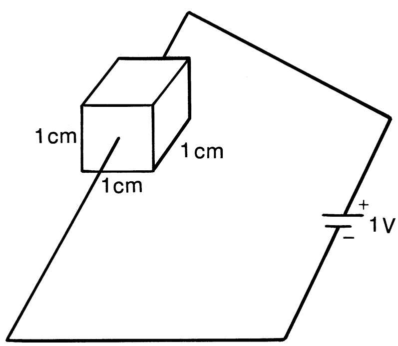

FIGURE 22.5 Illustration showing how to use the law of resistance to get resistivity. *From a sketch by Don Kirkham.*

pp. 2587–2593). For example, the resistivity of aluminum at 20 °C is 2.828×10^{-6} Ω-cm. The resistivity of copper at 20 °C is 1.77×10^{-6} Ω-cm. The resistivity of gold at 20 °C is 2.44×10^{-6} Ω-cm. The resistivity of silver at 18 °C is 1.629×10^{-6} Ω-cm.

22.4 UNITS OF ELECTRICAL CONDUCTIVITY

Electrical conductivity is used to measure the salinity of a soil. Old units of electrical conductivity were mmhos per centimeter; the United States Department of Agriculture (USDA) Handbook No. 60 (1954), edited by L.A. Richards, is still in use for standard measurements of saline soils, uses the old unit of mmhos per centimeter. We need to know how to convert mmhos per centimeter into SI units. The SI unit for conductance is the Siemens. (For biographies of members of the Siemens family, see the Appendix, Section 22.10.) Conductance is $1/R$, and its non-SI unit is the mho, which is ohm spelled backward.

$$1 \text{ Siemen} = 1/R = 1/1 \text{ ohm} = 1 \text{ mho}.$$

The SI unit for electrical conductivity is the decisiemen per meter.

$$1 \text{ decisiemen/m} = 1 \text{ dS/m} = 1 \text{ mmho/cm}.$$

Example: Assume that we have saltwater in a container that is 24 cm long and 5 cm wide. The saltwater stands to a height of 9 mm in the container. We measure a resistance of 400 Ω with a Wheatstone bridge. What is the conductance? What is the electrical conductivity? (Hint: From the law of resistance, get resistivity and take its reciprocal.)

Conductance = 1/400 Ω =0.0025 mhos.

Area = 0.9×5 cm = 4.5 cm^2.

400 Ω = (ρ 24 cm)/4.5 cm^2.

ρ = 75 Ω-cm. This is the resistivity.

1/75 Ω-cm = 0.013 mho/cm = 13 mmho/cm = 13 dS/m. This is the electrical conductivity.

22.5 EXAMPLE OF AN ELECTRICAL ANALOG APPLIED TO SOIL WITH WORMHOLES

The same container cited in the preceding example (24 cm long and 5 cm wide) was used to determine, in an electrical-analog study, the water and air conductance in soil with earthworms (Kirkham, 1982). The objective was to quantify the relationship between conductance and wormholes of different sizes oriented in the horizontal and vertical directions, which simulated wormholes oriented horizontally to the soil

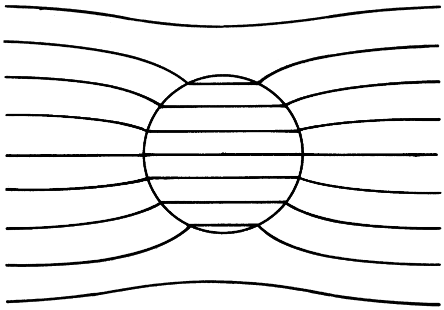

FIGURE 22.6 Electrical analog of oxygen-flow concentration or nutrient-flow concentration (flow lines are close together) in an isolated vertical wormhole with flow perpendicular to the hole axis. The figure is for a conductivity in the "wormhole" equal to five times that in the soil. *From Smythe (1950, p. 68). This material is reproduced with permission of The McGraw-Hill Companies.*

surface or perpendicularly to the soil surface. Copper pipes of different diameters, placed horizontally and vertically in the center of the electrolyte (tap water) in the container, simulated the wormholes. The results showed that wormholes, when their diameter and/or length is increased, cause an increase in soil conductance. Large increases (e.g., 100%) in conductance did not occur for holes in the vertical direction (and flow perpendicular to the holes) until a hole had a diameter that was >70% of the length of the unit volume. Similarly, large increases in conductance did not occur in the horizontal direction unless the wormhole length was an appreciable amount of the soil length associated with the hole.

The experiment simulated the concentration of oxygen in the moving air, or nutrients in the moving soil water, in the wormholes (Figure 22.6). The increased concentration of oxygen in air, or nutrients in water, may be one reason why roots concentrate in wormholes. The increased concentration of oxygen or nutrients in the hole will occur even when the wormholes are not directly connected to the soil surface, as was the case in this experiment (Kirkham, 1982). The experiment showed that electrical-analog studies can provide information that is not easily measured in the field.

22.6 VAN DEN HONERT'S EQUATION

The analogy for water movement through the entire SPAC and the flow of electricity has been discussed in the literature for decades. According to van den Honert (1948), "It was Gradmann's (1928) idea to apply an analogue of Ohm's law to this water transport as a whole". However, if one looks at the Gradmann paper, one sees no place where Ohm is mentioned. So Gradmann must have suggested a linear flow law, such as

Ohm's law, without mentioning Ohm specifically. We remember that Ohm's law is one of the linear flow laws that is so important in transport (Table 7.1). Kramer (1983, p. 190) cites Huber (1924) as the originator of the idea, and also lists Gradmann (1928) as one who developed it. Despite the uncertainty about who originated the idea that water flow through the soil–plant–atmosphere system is similar to the flow of electricity, the paper published by van den Honert (1948) (in English) is the most cited paper on the topic.

Let us first look at the more simple form of Ohm's law in Eqn (22.1), $V = IR$. A current I of electricity exists in a conductor whenever electric charge q is being transferred from one point to another in that conductor. If charge is transferred at a uniform rate of 1 C per second, then the constant current existing in the conductor is 1 A (Schaum, 1961, pp. 146–147). The potential difference V between two points in a conductor is measured by the work W required to transfer unit charge from one point to the other. The volt is the potential difference between two points in a conductor when 1 J of work is required to transfer 1 C of charge from one point to the other. The resistance R of a conductor is the property that depends on its dimensions, material, and temperature, and that determines the current produced in it by a given potential difference. The *ohm* is the resistance of a conductor in which there is a current of 1 A when the potential difference between its ends is 1 V. Ohm's law states that the value of the steady electrical current I in a metallic conductor at a constant temperature is equal to the potential difference V between the ends of the conductor divided by the resistance R of the conductor (Figure 22.7), or

$$I \text{ (current)} = V \text{ (potential difference)}/R \text{ (resistance)}, \tag{22.5}$$

$$I \text{ (amperes)} = V \text{ (volts)}/R \text{ (ohms)}.$$

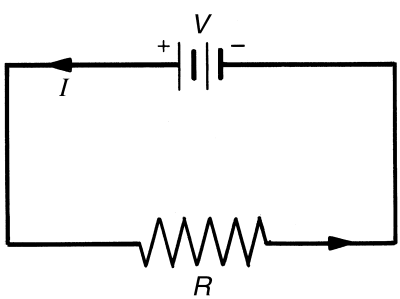

FIGURE 22.7 Diagram illustrating Ohm's law. *Adapted from Schaum (1961, p. 149). This material is reproduced with permission of The McGraw-Hill Companies.*

Ohm's law may be applied to any part of a circuit or to the entire circuit. Thus, the potential difference, or voltage drop, across any part of a conductor is equal to the current I in the conductor multiplied by the resistance R of that part, or $V = IR$. When Ohm's law is applied to the SPAC, the following analogies are made:

V is the potential difference between any two parts in the system. The potential in each part of the system is the (total) water potential (Ψ_w), which is measured, for example, with a thermocouple hygrometer or pressure chamber and is usually expressed using the unit of megapascals.

I is the flow of water (transpiration rate). This is what Nobel (e.g., 1974, p. 142) calls J_v or volume flow measured in units such as meters per second.

R is the resistance. Its units depend upon how V (or Ψ_w) and I have been defined.

van den Honert (1948) uses the Ohm's law analogy to develop an equation similar to the following, which Baker (1984, p. 310) modified using modern terminology (Ψ in place of the old terminology of diffusion pressure deficit, which van den Honert used):

$$\begin{aligned} J_v &= (\Delta\Psi)/r = (\Psi_{\text{soil}} - \Psi_{\text{root}})/r_1 = (\Psi_{\text{root}} - \Psi_{\text{stem}})/r_2 \\ &= (\Psi_{\text{stem}} - \Psi_{\text{leaf}})/r_3 = (\Psi_{\text{leaf}} - \Psi_{\text{air}})/r_4 \\ &= (\Psi_{\text{soil}} - \Psi_{\text{air}})/(r_1 + r_2 + r_3 + r_4), \end{aligned} \tag{22.6}$$

where J_v is the steady rate of water flow, Ψ is the water potential at different parts in the system (the subscript designates the location), and r_1, r_2, r_3, and r_4 are the resistances between the soil and root, the root and stem, the stem and leaf, and the leaf and air, respectively. This equation has been reproduced in many textbooks (e.g., see Kramer, 1983, p. 190).

22.7 PROOF OF VAN DEN HONERT'S EQUATION

It is not obvious why the string of equations in Eqn (22.6) should equal each other. In fact, some have questioned the "equal" signs in Eqn (22.6) and suggested that they should be "plus" signs. So we shall now prove Baker's (van den Honert's) equation (Eqn (22.6)), or we shall prove that

$$J_v = (\Psi_{\text{soil}} - \Psi_{\text{air}})/(r_1 + r_2 + r_3 + r_4).$$

We divide up the string of equations into individual equations.

$$J_v = (\Psi_{\text{soil}} - \Psi_{\text{root}})/r_1, \tag{22.7}$$

$$J_v = (\Psi_{\text{root}} - \Psi_{\text{stem}})/r_2, \tag{22.8}$$

$$J_v = (\Psi_{stem} - \Psi_{leaf})/r_3, \tag{22.9}$$

$$J_v = (\Psi_{leaf} - \Psi_{air})/r_4. \tag{22.10}$$

We now multiply the first equation (Eqn (22.7)) through by r_1; Eqn (22.8) through by r_2; Eqn (22.9) through by r_3; and Eqn (22.10) through by r_4:

$$J_v r_1 = (\Psi_{soil} - \Psi_{root}), \tag{22.11}$$

$$J_v r_2 = (\Psi_{root} - \Psi_{stem}), \tag{22.12}$$

$$J_v r_3 = (\Psi_{stem} - \Psi_{leaf}), \tag{22.13}$$

$$J_v r_4 = (\Psi_{leaf} - \Psi_{air}). \tag{22.14}$$

In Eqns 22.11–22.14, we add up the left sides and add up the right sides and then equate the resultant left and right sides to get one equation (Eqn (22.15)):

$$\begin{aligned} J_v r_1 + J_v r_2 + J_v r_3 + J_v r_4 = {} & (\Psi_{soil} - \Psi_{root}) + (\Psi_{root} - \Psi_{stem}) \\ & + (\Psi_{stem} - \Psi_{leaf}) + (\Psi_{leaf} - \Psi_{air}). \end{aligned} \tag{22.15}$$

We now cancel units in Eqn (22.15) and factor the left-hand side.

$$J_v(r_1 + r_2 + r_3 + r_4) = \Psi_{soil} - \Psi_{air}. \tag{22.16}$$

We divide each side of Eqn (22.16) by $(r_1 + r_2 + r_3 + r_4)$:

$$J_v(r_1 + r_2 + r_3 + r_4)/(r_1 + r_2 + r_3 + r_4) = (\Psi_{soil} - \Psi_{air})/(r_1 + r_2 + r_3 + r_4). \tag{22.17}$$

We simplify the left-hand side of Eqn (22.17) and get the equation as shown by Baker (1984):

$$J_v = (\Psi_{soil} - \Psi_{air})/(r_1 + r_2 + r_3 + r_4)\ \text{QED}.$$

(QED is used in mathematics, and it is Latin for "quod erat demonstrandum" or "which was to be proved".)

22.8 APPENDIX: BIOGRAPHY OF GEORG OHM

Georg Simon Ohm (1789–1854) was an ingenious German investigator who, although removed from the influence of personal contact with the renowned physicists of his time and working independently and alone, discovered the great law bearing his name (Cajori, 1929, p. 234). He was born in Erlangen on March 16, 1787, and was educated at the university there (Preece, 1971, cited under Ohm). He then taught school at Gottstadt, Neufchâtel, and Bamberg. In 1817, he became teacher of mathematics and physics in the Jesuits' college in Cologne, and taught there for nine years with great success. A pupil of that time, who later attained fame as a mathematician, was Lejene Dirichlet (1805–1859).

Ohm wanted to do research, but the want of leisure and books, as well as the lack of suitable apparatus, made progress difficult. The mechanical skill that he had acquired as a boy from his father, a locksmith, enabled him to construct much apparatus for himself (Cajori, 1929, p. 235).

Ohm's first experiments were on the relative conductivity of metals. In these tests, he was troubled by variations in his batteries ("Wogen der Kraft" or "surge in power"). He adopted thermoelectric elements as the sources of current that were free from this trouble. He published the experimental results that were the basis for his famous law in 1826. The following year he published a book entitled *Die galvanische Kette, mathematisch bearbeitet* (Mathematical Work on the Galvanic Chain) published in Berlin, 1827. It contained a theoretical deduction of his law, and became far more widely known than his article of 1826, giving the experimental deduction. There was unfavorable reception of his conclusions. In the Berlin *Jahrbücher für wissenschafliche Kritik*, Ohm's theory was "named a web of naked fancies, which can never find the semblance of support from even the most superficial observation of facts; he who looks on the world with the eye of reverence must turn aside from this book as the result of an incurable delusion, whose sole effort is to detract from the dignity of nature" (Cajori, 1929, p. 238).

Because Ohm's great ambition was to secure a university professorship, we can understand how this criticism affected him. To write his book of 1827, he had secured leave of absence and had gone to Berlin, where the library facilities were better than at Cologne. Not only did he fail to secure promotion by the publication of his book but he also incurred the ill will of a school official, who was a supporter of Hegelianism and, therefore, opposed to experimental research. In consequence, Ohm resigned his position in Cologne (Cajori, 1929, p. 238).

For six years, Ohm lived in Berlin, giving three mathematical lessons a week in the *Kriegsschule* for a small salary. In 1833, he obtained an appointment at the polytechnic in Nürnberg. Gradually, his electric researches called forth respect and admiration, particularly from foreigners, including Gustav Fechner (1801–1887) in Germany, Wheatstone in England (Section 22.9), Heinrich Lenz (1804–1865) in Russia, and Joseph Henry (1797–1878) in America. In 1841, the Royal Society of London awarded him its Copley Medal, and, in 1842, it made him a foreign member. Ohm's experience reminds us of the biblical saying, "A prophet is not without honor, save in his own country" (Matthew 13:57).

In 1849, at the age of 62, the ambition of Ohm's youth was finally attained. He was appointed extraordinary professor at the University of Munich and, in 1852, ordinary professor. His writings were numerous. In addition to a number of papers on mathematical subjects, Ohm wrote a textbook, *Grundzuge der Physik* (Main Features of Physics) (1854). He died in Munich on July 7, 1854 (Preece, 1971).

22.9 APPENDIX: BIOGRAPHY OF CHARLES WHEATSTONE

Sir Charles Wheatstone (1802–1875) was an English physicist whose name is associated with the Wheatstone bridge for measuring electrical resistance. He was born near Gloucester in February 1802. He became a manufacturer of musical instruments, but in 1834 accepted the chair of experimental physics at King's College, London. At about this time, Wheatstone measured (with a revolving mirror) the great speed of electric discharge in conductors. Applying this speed for sending messages, he and William Fothergill Cooke (1806–1879, an English inventor) patented an early form of electric telegraph in 1837. Wheatstone's inventions included a cryptographic machine, the concertina (a small musical instrument of the accordion type, with bellows and keys), and a form of stereoscope. He wrote papers on the transmission of sound in solids and on the physiology of vision, binocular vision, and color. Wheatstone showed that the electrical sparks from different metals give different spectra. He played a prominent part in the early development of electric generators and of telegraphy with submarine cables (Preece, 1971, cited under Wheatstone).

Wheatstone, a great admirer of Ohm, perceived the necessity of more accurate means of measuring resistances. The measurement of resistance had been brought to perfection chiefly by those interested in the development of the telegraph. Wheatstone invented the rheostat, but this had been superseded by the resistance box. The earlier methods of measuring resistance had the defect of depending on the constancy of the batteries used (Cajori, 1929, p. 239). Wheatstone overcame the trouble by adopting a method suggested in 1833 by Samuel Hunter Christie (1784–1865; British mathematician) (Marquis Who's Who, 1968). A footnote in a book by James Clerk Maxwell (1892, p. 495) states, "Sir Charles Wheatstone, in his paper on 'New Instruments and Processes,' *Phil. Trans.*, 1843, brought this arrangement [Wheatstone's bridge] into public notice, with due acknowledgment of the original inventor, Mr. S. Hunter Christie, who had described it in his paper on 'Induced Currents,' *Phil. Trans.*, 1833, under the name of a Differential Arrangement".

Wheatstone was an experimentalist of extraordinary skill, but disliked speaking in public. In fulfillment of his duties at King's College he delivered a course of eight lectures on sound, but his habitual (though unreasonable) distrust of his own powers of speech proved to be an invincible obstacle, and he soon discontinued his lectures. Nevertheless, he retained the professorship for many years. In private, people were charmed by his able and lucid exposition, but in public, including at the Royal Society, his attempt to repeat the same information invariably proved unsatisfactory (Cajori, 1929, p. 239). For this reason, some of his more important investigations were brought before the Royal Society by Faraday.

Wheatstone's *Scientific Papers* were collected and published by the Physical Society of London in 1879. Wheatstone retired to private life, living on the income from his inventions, particularly that of the telegraph. He died in Paris on October 19, 1987 (Preece, 1971, cited under Wheatstone).

22.10 APPENDIX: BIOGRAPHIES OF MEMBERS OF THE SIEMENS FAMILY

There were four important men in the Siemens family: Werner, William, Friedrich, and Alexander.

Werner von Siemens (1816—1892) was the chief founder of the electrical firm with his name. He was born on December 13, 1816, at Lenthe, Hanover, Germany. Between 1838 and 1848, he held a commission in the artillery, was entrusted with many specialized undertakings, and, in particular, became acquainted with the recently developed electric telegraph. In 1847, he founded, together with skilled mechanic J.G. Halske, the firm of Siemens and Halske for the manufacture of telegraphic apparatus. This firm, under Siemens's guidance, became one of the most important electrical companies in the world, with branches in different countries. The branches in England and Russia were particularly important. It carried out large telegraphic projects and expanded into other electrical fields, as new applications of electricity were developed (Weston, 1971).

Many of Werner von Siemens's inventions related to telegraphic apparatus. He used gutta-percha, a rubberlike substance from trees in Malaysia, as an insulator for telegraphic cable in 1847. This form of insulation was later widely used for electric-light cables. The Siemens armature, which he invented in 1856 for use in telegraphy, was used in large generators and has evolved into the modern armature. One of the most important of Siemens's discoveries was that of the dynamoelectric principle, which governs the self-excitation of the dynamo. He died at Charlottenburg, Berlin, on December 6, 1892 (Weston, 1971).

Sir William Siemens (Karl Wilhelm; 1823—1883) was Werner's brother and is known for his work in electricity and in the application of heat. In both fields, he combined the functions of innovator, manufacturer, and successful businessman. He was born at Lenthe, Hanover, on April 4, 1823. After attending the University of Göttingen, he entered, as a pupil, the manufacturing concern of Count Stolberg at Magdeburg. At the age of 19, he first visited England in the hope of introducing an electroplating process invented by himself and Werner, which he succeeded in selling. He returned to Germany, but in 1844 was again in England, this time with another invention, the "chronometric", or differential, governor. Finding that British patent law afforded the inventor a protection then lacking in Germany, he henceforth made England his home.

The next few years were spent in trying to develop his inventions, of which at this time his water meter was commercially the most successful. His activities made him a respected figure in scientific circles. His paper "On the Conservation of Heat Into Mechanical Effect", read to the Institution of Civil Engineers in 1853, gained him the Telford Medal, and in 1862, he was elected a member of the Royal Society. William's chief work in the field of heat was concerned with regenerative heating and consequent improvements in steelmaking processes.

In the field of electricity, William became an acknowledged authority and leader. From 1848 onward, he represented the firm of Siemens and Halske in London, and when in 1865 the separate firm of Siemens Brothers was established, he became a partner and director. At first, the chief business was the erection of overland telegraph lines and the laying of submarine telegraph cables. William was, however, in constant close liaison with all the ideas and projects of his brother Werner in Berlin and, when the latter discovered the dynamoelectric principle, William introduced it to England by reading a paper about it to the Royal Society in 1867. Gradually, in the late 1870s and 1880s, the electric-light side of the business grew. One of the last projects with which William was associated was the Portrush electric railway in the north of Ireland, opened in 1883, which utilized water turbines driving a Siemens dynamo. William Siemens was knighted in 1883, and he died in London the same year on November 19 (Weston, 1971).

Friedrich Siemens (1826—1904) was the brother of Werner and William. He was born in Mentzendorff, Germany, on December 8, 1826 (Marquis Who's Who, 1968). Friedrich, along with William, first tried to apply the regenerative condenser to the steam engine, using the heat from the regenerator to preheat the boiler feed water. When this did not succeed, other applications were sought and the idea occurred of applying the principle to furnaces, using the heat regained from the flue gases to heat the air supply to the furnace. This was patented by Friedrich in 1856 and met with great success for use both in glassmaking and in steel manufacture. Later, the use of gas instead of solid fuel greatly extended the use of the regenerative furnace (Weston, 1971). He died in May 26, 1904.

Alexander Siemens (1847—1928), William's nephew, was born in Hanover, Germany, on January 22, 1847. In 1867, he went to England, where he worked first in the workshops of Siemens Brothers at Woolwich, and then in the erection of the Indo-European telegraph line in Persia (1868) and in the laying of the Black Sea cable (1868). In 1878, he became a naturalized British subject. The following year he took over the management of the electric-light department of Siemens Brothers, and was responsible for the installation of electric light at Godalming, Surrey, the first English town to be so lighted.

Like many other members of the family, Alexander patented several inventions. After the death of Sir William, he became a director of the company, a position he retained until 1918. He took an active part in public activities associated with his profession, was a member of several important committees, and was twice president of the Institution of Electrical Engineers. He died at Milford-on-Sea, Hampshire, on February 16, 1928 (Weston, 1971).

Siemens is still an important name in business today, and the company is often noted in *The Wall Street Journal*.

References

Baker, D.A., 1984. Water relations. In: Wilkins, M.B. (Ed.), Advanced Plant Physiology. Pitman, London, pp. 297–318.

Cajori, F., 1929. A History of Physics. Macmillan, New York.

Clerk Maxwell, J., 1892. A Treatise on Electricity and Magnetism, vol. II. Reprinted 1904. Oxford University Press, London (Reprinted photographically in Great Britain in 1937 by Lowe and Brydone, Printers, London, from sheets of the Third edition.).

Gradmann, H., 1928. Untersuchungen über die Wasserverhältnisse des Bodens als Grundlage des Pflanzenwachstums. Jahrbucher für Wissenschaftliche Botanik 69, 1–100.

Hausmann, E., Slack, E.P., 1948. Physics. D. Van Nostrand, New York.

Hodgman, C.D., 1959. Handbook of Chemistry and Physics, fortieth ed. Chemical Rubber Publishing, Cleveland, Ohio.

Huber, B., 1924. Die Beurteilung des Wasserhaushaltes der Pflanze. Ein Beitrag zur vergleichenden Physiologie. Jahrbucher für Wissenschaftliche Botanik 64, 1–120.

Ingersoll, L.R., Martin, M.J., Rouse, T.A., 1953. A Laboratory Manual of Experiments in Physics. McGraw-Hill, New York.

Kirkham, D., Powers, W.L., 1972. Advanced Soil Physics. Wiley, New York.

Kirkham, M.B., 1982. Water and air conductance in soil with earthworms: an electrical-analogue study. Pedobiologia 23, 367–371.

Kirkham, M.B., 2002. The concept of the soil–plant–atmosphere continuum and applications. In: Raats, P.A.C., Smiles, D., Warrick, A.W. (Eds.), Environmental Mechanics: Water, Mass and Energy Transfer in the Biosphere, Geophysical Monograph, vol. 129. American Geophysical Union in Cooperation with CSIRO, Australia, pp. 327–335 (American Geophysical Union: Washington, D.C).

Kramer, P.J., 1983. Water Relations of Plants. Academic Press, New York.

Marquis Who's Who, 1968. Who's Who in Science from Antiquity to the Present, first ed. Marquis-Who's Who, Chicago.

Nobel, P.S., 1974. Introduction to Biophysical Plant Physiology. W.H. Freeman, San Francisco.

Ohm, Georg Simon, 1971. In: Preece, W.E. (Ed.), Encyclopaedia Britannica, General ed., vol. 16, pp. 896–897.

Philip, J.R., 1957. The Physical Principles of Soil Water Movement during the Irrigation Cycle. International Commission on Irrigation and Drainage, Third Congress, Algiers. R. 7, Question 8, 8.125–8.154.

Philip, J.R., 1966. Plant water relations: some physical aspects. Annu. Rev. Plant Physiol. 17, 245–268.

Schaum, D., 1961. Schaum's Outline of Theory and Problems of College Physics, sixth ed. Schaum, New York.

Slichter, C.S., 1899. Theoretical investigations of the motion of ground-water. US Geol. Surv. Annu. Rep. 19, 295–384.

Smythe, W.R., 1950. Static and Dynamic Electricity, second ed. McGraw-Hill, New York.

United States Department of Agriculture, 1954. Diagnosis and Improvement of Saline and Alkali Soils. In: Richards, L.A. (Ed.), Agr Handbook No. 60. United States Department of Agriculture, Washington, DC.

van den Honert, T.H., 1948. Water transport in plants as a catenary process. Discuss. Faraday Soc. 3, 146–153.

Wheatstone, Sir Charles, 1971. In: Preece, W.E. (Ed.), Encyclopaedia Britannica, General ed., vol. 23, p. 473.

Weston, M.K., 1971. Siemens. Encyclopaedia Britannica vol. 20, 484–485.