Adv Physiol Educ 42: 260–262, 2018;
doi:10.1152/advan.00006.2018.

ILLUMINATIONS

Flowcharts to aid student comprehension of Nernst equation calculations

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Submitted 4 January 2018; accepted in final form 28 February 2018

INTRODUCTION

The ability to understand calculations involving the Nernst equation is a fundamental skill expected of all students studying excitable membranes. The typical scenario encountered by students involves an intracellular compartment separated from the extracellular fluid by a semipermeable membrane (7). Under these conditions, the Nernst equation can be expressed as:

$$E_X = \frac{RT}{zF}\ln\frac{[X]_o}{[X]_i} = \frac{61.5}{z}\log_{10}\frac{[X]_o}{[X]_i}$$

where E_X is the reversal potential; $[X]_o$ and $[X]_i$ are the extracellular and intracellular ion concentrations, respectively; z is the valence of the ion; R is the gas constant; T is the absolute temperature; and F is Faraday's constant (7), initially reducing to the factor 26.7 mV at 37°C, then to 61.5 mV, if $\log_{10}$ rather than ln is used, since $\log_{10}x = \ln x/\ln 10$. The equation and its utility in determining membrane potential (E_m) are considered sufficiently important to justify dedicated chap-

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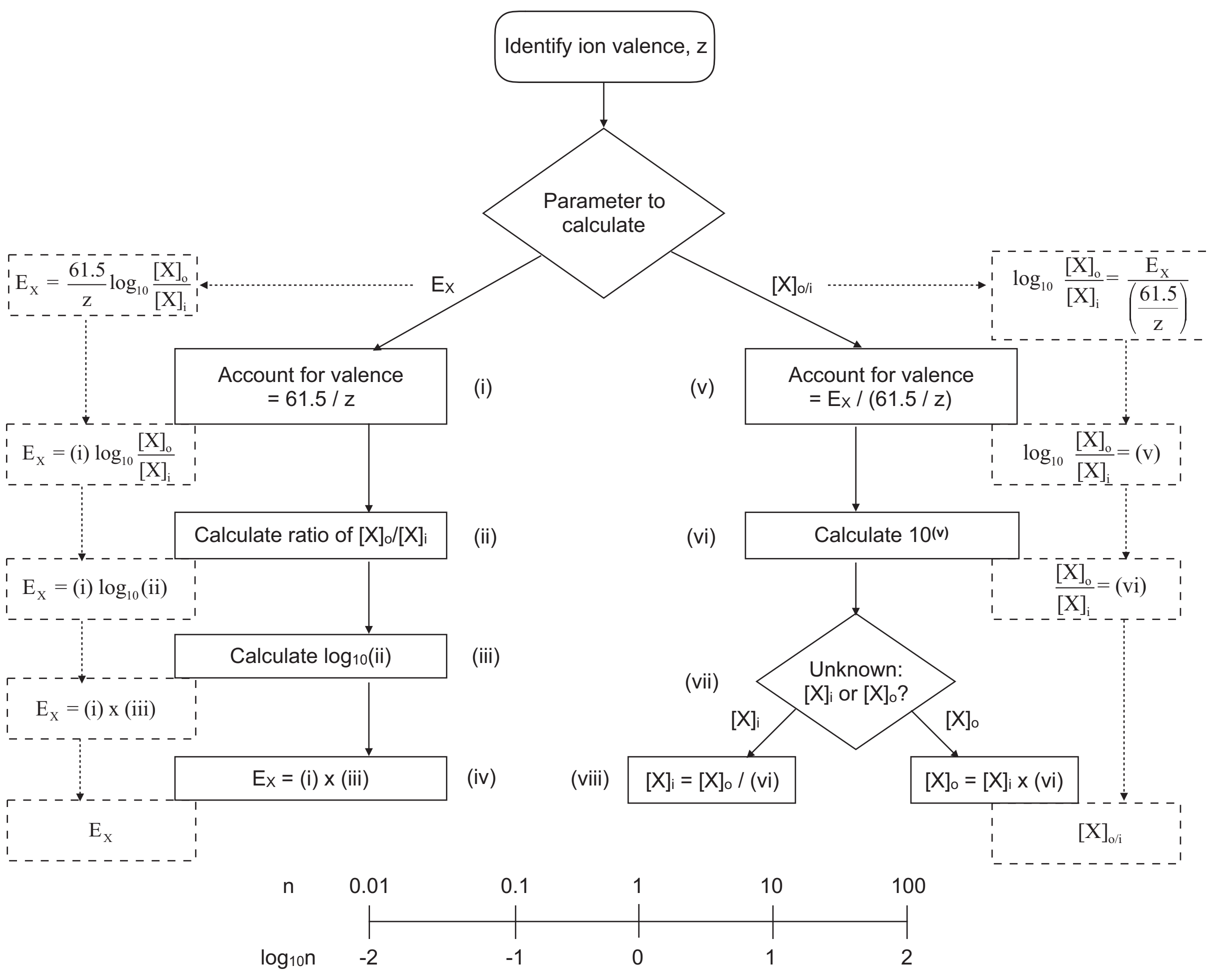

Fig. 1. The template, which follows conventional flowchart symbols, illustrates the sequence of steps and decisions required to complete the data flow process. The Roman numerals in parentheses represent the individual steps in the process, which are used to calculate any of the three parameters in the Nernst equation, if the two other parameters are known. The equations, contained within the dashed boxes, are placed underneath the corresponding steps and denote progress of the calculation. The parameters in the equation are replaced by the relevant Roman numerals upon sequential completion of the appropriate step. A $\log_{10}$ conversion scale is included to facilitate *steps iii* and *vi*.

ters in textbooks (2, 8, 11, 12) and has been the subject of numerous articles in this (3–6, 9, 10, 13, 14, 16) and other journals (1, 15). Although the Nernst equation contains only three parameters, it is the cause of much student anguish, an issue I attempted to address in a recent publication regarding the logarithmic transformation that lies at the heart of the Nernst equation (13). Reflecting on that publication while teaching the topic to current second-year undergraduate neuroscience students prompted me to develop a flowchart to help students understand the logical sequence of steps that are required to satisfactorily implement calculations involving the Nernst equation. This chart can be used as a template to calculate any of the three parameters in the Nernst equation, providing the two other parameters are known. Thus, when $[X]_o$ and $[X]_i$ are known, E_X can be calculated, and $[X]_o$ or $[X]_i$ can be calculated if E_X and the other compartmental ion concentration are known.

The flowchart, illustrated in Fig. 1, requires as an initial step identifying the valence of the ion under investigation, followed by selection of the parameter to be calculated (E_X or $[X]_{o/i}$), which dictates the direction of flow. For the sake of clarity, I have assumed that all calculations are carried out at 37°C. If we assume that E_X is the unknown parameter and $[X]_o$ and $[X]_i$ are known (*left* branch of the chart), the factor 61.5 mV must be modified according to the ions valence (*step i*). The ratio of $[X]_o$ and $[X]_i$ is calculated (*step ii*), the result of which is then logarithmically transformed (*step iii*). It is then a simple matter of multiplying the result of *steps i* and *iii* to return the value for E_X (*step iv*). This procedure works for anions and cations of any valence. The alternate calculation initially appears more complex, since E_X and the ion concentration in only one compartment are known (*right* branch of the chart). This calculation requires rearrangement of the standard form in which the Nernst equation is usually expressed (see above), such that the ratio $[X]_o/[X]_i$ is isolated on one side of the equation. E_X is then divided by the factor 61.5, scaled according to the valence of the ion (*step v*), then the ratio of $[X]_o$ and $[X]_i$ that yields E_X forms the exponent of the base 10 (*step vi*), since $\log_{10}x = a$ is equivalent to $10^a = x$. Retaining natural logarithms in the Nernst equation has two consequences in our scheme, requiring the factor 61.5 mV to be divided by ln 10 to revert to 26.7 mV (see above), and transforming *step vi* to $e^{(v)}$, since $\ln x = a$ is equivalent to $e^a = x$. Whether $[X]_o$ or $[X]_i$ is the unknown quantity (*step vii*) determines the subsequent scaling of the known ion concentration (*step viii*) by the result calculated in *step vi*. When teaching students calculations involving base 10 logs, I have found that maintaining an order of magnitude difference between $[X]_o$ and $[X]_i$, e.g., 20 mM and 200 mM, simplifies the arithmetic to the extent that calculators are not required.

A flowchart that allows investigation of the effect of temperature on E_X is illustrated in Fig. 2. As above, the initial stage is to identify the valence of the ion, followed by rearrangement of the equation to isolate T from the other constants (*step i*). Sequential solving of R/zF (*step ii*), calculating the ratio of $[X]_o/[X]_i$ (*step iii*), logarithmically transforming this ratio (*step iv*), and then multiplying by *step ii* produces a quantity that, when multiplied by the desired temperature, allows the calculation of E_X as a factor of temperature (*step v*).

In conclusion, I suggest that these templates be used in conjunction with recently published articles in this journal

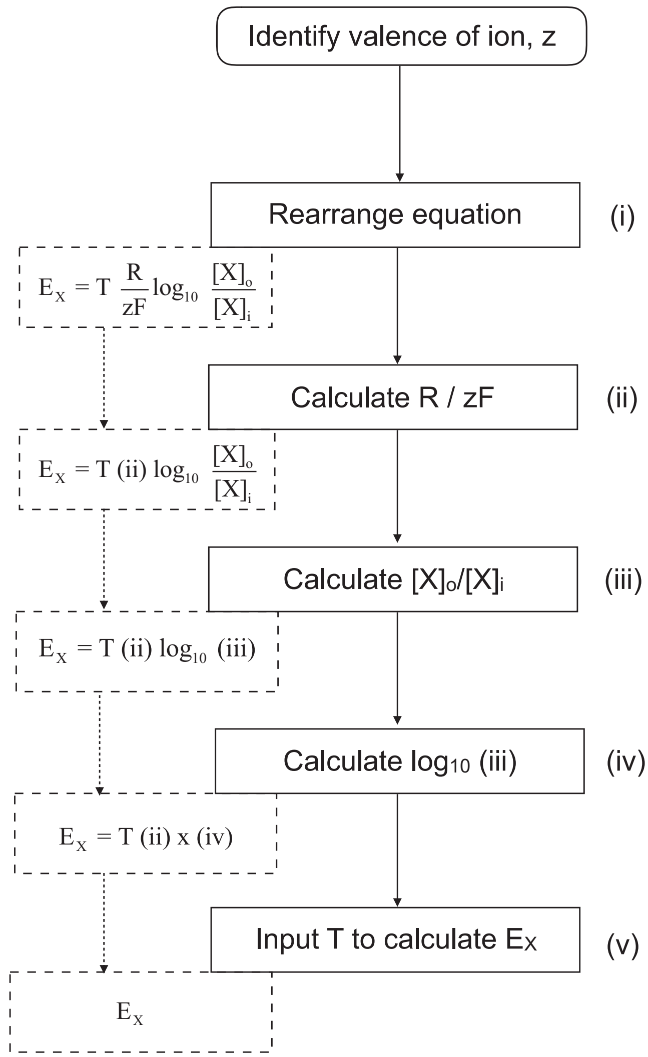

Fig. 2. A template for investigating the effect of temperature on E_X. The sequential steps are completed in the manner described for Fig. 1.

that describe the concept of the Nernst equation (3), logarithmic transformation as applied to the Nernst equation (13), and the direction of ion flow that occurs when E_X is not equal to E_m (5).

ACKNOWLEDGMENTS

I am grateful to the current cohort of second-year neuroscience students at the University of Nottingham whose insightful comments precipitated this paper.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author.

AUTHOR CONTRIBUTIONS

A.M.B. conceived and designed research, interpreted results of experiments, prepared figures, drafted manuscript, edited and revised manuscript, approved final version of manuscript.

REFERENCES

1. **Barry PH.** Membrane potential simulation program for IBM-PC-compatible equipment for physiology and biology students. *Am J Physiol* 259: S15–S23, 1990. doi:10.1152/advances.1990.259.6.S15.

2. **Bear MF, Connors BW, Paradiso MA.** The neuronal membrane at rest. In: *Neuroscience: Exploring the Brain* (4th Ed.), edited by Bear MF, Connors BW, Paradiso MA. Philadelphia, PA: Wolters Kluwer, 2016, p. 55–80.
3. **Cardozo D.** An intuitive approach to understanding the resting membrane potential. *Adv Physiol Educ* 40: 543–547, 2016. doi:10.1152/advan.00049.2016.
4. **Cardozo DL.** A model for understanding membrane potential using springs. *Adv Physiol Educ* 29: 204–207, 2005. doi:10.1152/advan.00067.2004.
5. **Crowther GJ.** Which way do the ions go? A graph-drawing exercise for understanding electrochemical gradients. *Adv Physiol Educ* 41: 556–559, 2017. doi:10.1152/advan.00111.2017.
6. **Dwyer TM, Fleming J, Randall JE, Coleman TG.** Teaching physiology and the World Wide Web: electrochemistry and electrophysiology on the Internet. *Am J Physiol* 273: S2–S13, 1997. doi:10.1152/advances.1997.273.6.S2.
7. **Hille B.** *Ion Channels of Excitable Membranes*. Sunderland, MA: Sinauer, 2001.
8. **Kandel ER, Schwartz JH, Jessell TM, Siegelbaum SA, Hudspeth AJ.** Membrane potential and the passive electrical properties of the neuron. In: *Principles of Neural Science* (5th Ed.), edited by Kandel ER, Schwartz JH, Jessell TM, Siegelbaum SA, Hudspeth AJ. New York: McGraw Hill, 2013, p. 126–147.
9. **Milanick M.** Changes of membrane potential demonstrated by changes in solution color. *Adv Physiol Educ* 33: 230, 2009. doi:10.1152/advan.00052.2009.
10. **Moran WM, Denton J, Wilson K, Williams M, Runge SW.** A simple, inexpensive method for teaching how membrane potentials are generated. *Am J Physiol* 277: S51–S59, 1999. doi:10.1152/advances.1999.277.6.S51.
11. **Nicholls JG, Martin AR, Fuchs PA, Brown DA, Diamond ME, Weisblat DA.** Ionic basis of the resting potential. In: *From Neuron to Brain* (5th Ed.), edited by Nicholls JG, Martin AR, Fuchs PA, Brown DA, Diamond ME, Weisblat DA. Sunderland, MA: Sinauer, 2012, p. 99–128.
12. **Purves D, Augustine GJ, Fitzpatrick D, Hall WC, LaMantia A-S, White LE.** Electrical signals of nerve cells. In: *Neuroscience* (5th Ed.), edited by Purves D, Augustine GJ, Fitzpatrick D, Hall WC, LaMantia A-S, White LE. Sunderland, MA: Sinauer, 2012, p. 25–56.
13. **Sawyer JER, Hennebry JE, Revill A, Brown AM.** The critical role of logarithmic transformation in Nernstian equilibrium potential calculations. *Adv Physiol Educ* 41: 231–238, 2017. doi:10.1152/advan.00166.2016.
14. **Silverthorn DU.** Uncovering misconceptions about the resting membrane potential. *Adv Physiol Educ* 26: 69–71, 2002. doi:10.1152/advan.00012.2002.
15. **Thurman CL.** Resting membrane potentials: a student test of alternate hypotheses. *Am J Physiol* 269: S37–S41, 1995. doi:10.1152/advances.1995.269.6.S37.
16. **Wright SH.** Generation of resting membrane potential. *Adv Physiol Educ* 28: 139–142, 2004. doi:10.1152/advan.00029.2004.