

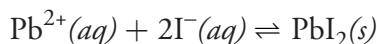
# Appendix

- Appendix 1: Normality
- Appendix 2: Propagation of Uncertainty and Uncertainty Budgets
- Appendix 3: Single-Sided Normal Distribution
- Appendix 4: Critical Values for the  $t$ -Test
- Appendix 5: Critical Values for the  $F$ -Test
- Appendix 6: Critical Values for Dixon's  $Q$ -Test
- Appendix 7: Critical Values for Grubb's Test
- Appendix 8: Recommended Primary Standards
- Appendix 9: Correcting Mass for the Buoyancy of Air
- Appendix 10: Solubility Products
- Appendix 11: Acid–Base Dissociation Constants
- Appendix 12: Metal–Ligand Formation Constants
- Appendix 13: Standard Reduction Potentials
- Appendix 14: Random Number Table
- Appendix 15: Polarographic Half-Wave Potentials
- Appendix 16: Countercurrent Separations
- Appendix 17: Review of Chemical Kinetics

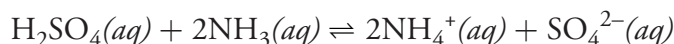
## Appendix 1: Normality

Normality expresses concentration in terms of the equivalents of one chemical species reacting stoichiometrically with another chemical species. Note that this definition makes an equivalent, and thus normality, a function of the chemical reaction. Although a solution of  $\text{H}_2\text{SO}_4$  has a single molarity, its normality depends on its reaction.

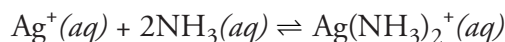
We define the number of equivalents,  $n$ , using a reaction unit, which is the part of a chemical species participating in the chemical reaction. In a precipitation reaction, for example, the reaction unit is the charge of the cation or anion participating in the reaction; thus, for the reaction



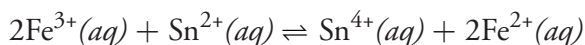
$n = 2$  for  $\text{Pb}^{2+}(\text{aq})$  and  $n = 1$  for  $2\text{I}^{-}(\text{aq})$ . In an acid–base reaction, the reaction unit is the number of  $\text{H}^{+}$  ions that an acid donates or that a base accepts. For the reaction between sulfuric acid and ammonia



$n = 2$  for  $\text{H}_2\text{SO}_4(\text{aq})$  because sulfuric acid donates two protons, and  $n = 1$  for  $\text{NH}_3(\text{aq})$  because each ammonia accepts one proton. For a complexation reaction, the reaction unit is the number of electron pairs that the metal accepts or that the ligand donates. In the reaction between  $\text{Ag}^{+}$  and  $\text{NH}_3$



$n = 2$  for  $\text{Ag}^{+}(\text{aq})$  because the silver ion accepts two pairs of electrons, and  $n = 1$  for  $\text{NH}_3$  because each ammonia has one pair of electrons to donate. Finally, in an oxidation–reduction reaction the reaction unit is the number of electrons released by the reducing agent or accepted by the oxidizing agent; thus, for the reaction



$n = 1$  for  $\text{Fe}^{3+}(\text{aq})$  and  $n = 2$  for  $\text{Sn}^{2+}(\text{aq})$ . Clearly, determining the number of equivalents for a chemical species requires an understanding of how it reacts.

Normality is the number of equivalent weights,  $EW$ , per unit volume. An equivalent weight is the ratio of a chemical species' formula weight,  $FW$ , to the number of its equivalents,  $n$ .

$$EW = \frac{FW}{n}$$

The following simple relationship exists between normality,  $N$ , and molarity,  $M$ .

$$N = n \times M$$

# **Appendix 2: Propagation of Uncertainty and Uncertainty Budgets**

## Appendix 3: Single-Sided Normal Distribution

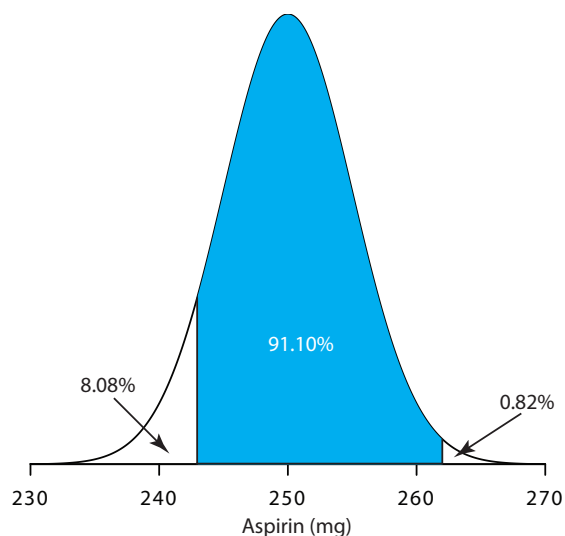
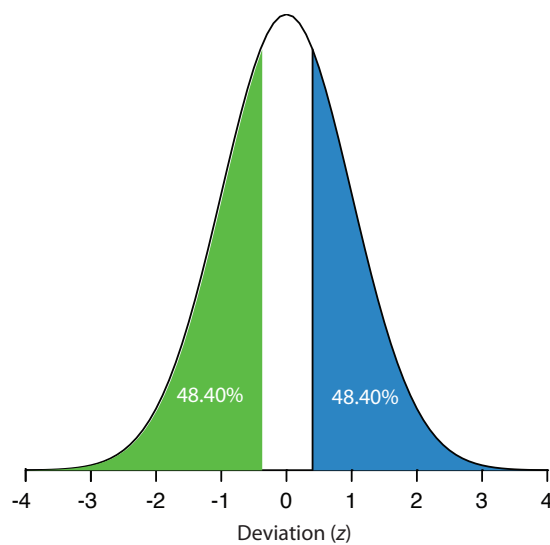
This table gives the proportion,  $P$ , of the area under a normal distribution curve to right of a deviation  $z$

$$z = \frac{X - \mu}{\sigma}$$

where  $X$  is the value for which the deviation is being defined,  $\mu$  is the distribution's mean value and  $\sigma$  is the distribution's standard deviation. For example, the proportion of the area under a normal distribution to the right of a deviation of 0.04 is 0.4840 (see entry in red), or 48.40% of the total area (see area shaded blue in the figure to the right). The proportion of the area to the left of the deviation is  $1 - P$ . For a deviation of 0.04, this is  $1 - 0.4840$ , or 51.60%.

When the deviation is negative—that is, when  $X$  is smaller than  $\mu$ —the value of  $z$  is negative. In this case, the values in the table give the area to the left of  $z$ . For example, if  $z$  is  $-0.04$ , then 48.40% of the area lies to the left of the deviation (see area shaded green in the figure to the right).

To use this table, sketch the normal distribution curve for your problem and shade the area corresponding to your answer (see figure to the left, which is for Example 4.11). This divides the normal distribution curve into three regions: the area corresponding to your answer (shown in blue), the area to the right of this, and the area to the left of this. Calculate the values of  $z$  for the limits of the area corresponding to your answer. Use the table to find the areas to the right and to the left of these deviations. Subtract these values from 100% and, volia, you have your answer.





## Appendix 4: Critical Values for $t$ -Test

Assuming you have calculated  $t_{\text{exp}}$ , there are two approaches to interpreting a  $t$ -test. In the first approach you choose a value of  $\alpha$  for rejecting the null hypothesis and read the value of  $t(\alpha, \nu)$  from the table shown below. If  $t_{\text{exp}} > t(\alpha, \nu)$ , you reject the null hypothesis and accept the alternative hypothesis. In the second approach, you find the row in the table below corresponding to your degrees of freedom and move across the row to find (or estimate) the  $\alpha$  corresponding to  $t_{\text{exp}} = t(\alpha, \nu)$ ; this establishes largest value of  $\alpha$  for which you can retain the null hypothesis. Finding, for example, that  $\alpha$  is 0.10 means that you would retain the null hypothesis at the 90% confidence level, but reject it at the 89% confidence level. The examples in this textbook use the first approach.

Values of $t$ for...				
...a confidence interval of:	90%	95%	98%	99%
...an $\alpha$ value of:	0.10	0.05	0.02	0.01
Degrees of Freedom				
1	6.314	12.706	31.821	63.657
2	2.920	4.303	6.965	9.925
3	2.353	3.182	4.541	5.841
4	2.132	2.776	3.747	4.604
5	2.015	2.571	3.365	4.032
6	1.943	2.447	3.143	3.707
7	1.895	2.365	2.998	3.499
8	1.860	2.306	2.896	3.255
9	1.833	2.262	2.821	3.250
10	1.812	2.228	2.764	3.169
12	1.782	2.179	2.681	3.055
14	1.761	2.145	2.624	2.977
16	1.746	2.120	2.583	2.921
18	1.734	2.101	2.552	2.878
20	1.725	2.086	2.528	2.845
30	1.697	2.042	2.457	2.750
50	1.676	2.009	2.311	2.678
$\infty$	1.645	1.960	2.326	2.576

The values in this table are for a two-tailed  $t$ -test. For a one-tail  $t$ -test, divide the  $\alpha$  values by 2. For example, the last column has an  $\alpha$  value of 0.005 and a confidence interval of 99.5% when conducting a one-tailed  $t$ -test.

# Appendix 5: Critical Values for the F-Test

The following tables provide values for  $F(0.05, \nu_{\text{num}}, \nu_{\text{denom}})$  for one-tailed and for two-tailed F-tests. To use these tables, decide whether the situation calls for a one-tailed or a two-tailed analysis and calculate  $F_{\text{exp}}$

$$F_{\text{exp}} = \frac{s_A^2}{s_B^2}$$

where  $s_A^2$  is greater than  $s_B^2$ . Compare  $F_{\text{exp}}$  to  $F(0.05, \nu_{\text{num}}, \nu_{\text{denom}})$  and reject the null hypothesis if  $F_{\text{exp}} > F(0.05, \nu_{\text{num}}, \nu_{\text{denom}})$ . You may replace  $s$  with  $\sigma$  if you know the population's standard deviation.

$F(0.05, \nu_{\text{num}}, \nu_{\text{denom}})$ for a One-Tailed F-Test													
$\frac{\nu_{\text{num}} \rightarrow}{\downarrow \nu_{\text{denom}}}$	1	2	3	4	5	6	7	8	9	10	15	20	$\infty$
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9	245.9	248.0	254.3
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.43	19.45	19.50
3	10.13	9.552	9.277	9.117	9.013	8.941	8.887	8.845	8.812	8.786	8.703	8.660	8.526
4	7.709	6.994	6.591	6.388	6.256	6.163	6.094	6.041	5.999	5.964	5.858	5.803	5.628
5	6.608	5.786	5.409	5.192	5.050	4.950	4.876	4.818	4.722	4.753	4.619	4.558	4.365
6	5.591	5.143	4.757	4.534	4.387	4.284	4.207	4.147	4.099	4.060	3.938	3.874	3.669
7	5.591	4.737	4.347	4.120	3.972	3.866	3.787	3.726	3.677	3.637	3.511	3.445	3.230
8	5.318	4.459	4.066	3.838	3.687	3.581	3.500	3.438	3.388	3.347	3.218	3.150	2.928
9	5.117	4.256	3.863	3.633	3.482	3.374	3.293	3.230	3.179	3.137	3.006	2.936	2.707
10	4.965	4.103	3.708	3.478	3.326	3.217	3.135	3.072	3.020	2.978	2.845	2.774	2.538
11	4.844	3.982	3.587	3.257	3.204	3.095	3.012	2.948	2.896	2.854	2.719	2.646	2.404
12	4.747	3.885	3.490	3.259	3.106	2.996	2.913	2.849	2.796	2.753	2.617	2.544	2.296
13	4.667	3.806	3.411	3.179	3.025	2.915	2.832	2.767	2.714	2.671	2.533	2.459	2.206
14	4.600	3.739	3.344	3.112	2.958	2.848	2.764	2.699	2.646	2.602	2.463	2.388	2.131
15	4.534	3.682	3.287	3.056	2.901	2.790	2.707	2.641	2.588	2.544	2.403	2.328	2.066
16	4.494	3.634	3.239	3.007	2.852	2.741	2.657	2.591	2.538	2.494	2.352	2.276	2.010
17	4.451	3.592	3.197	2.965	2.810	2.699	2.614	2.548	2.494	2.450	2.308	2.230	1.960
18	4.414	3.555	3.160	2.928	2.773	2.661	2.577	2.510	2.456	2.412	2.269	2.191	1.917
19	4.381	3.552	3.127	2.895	2.740	2.628	2.544	2.477	2.423	2.378	2.234	2.155	1.878
20	4.351	3.493	3.098	2.866	2.711	2.599	2.514	2.447	2.393	2.348	2.203	2.124	1.843
$\infty$	3.842	2.996	2.605	2.372	2.214	2.099	2.010	1.938	1.880	1.831	1.666	1.570	1.000

$F(0.05, \nu_{\text{num}}, \nu_{\text{denom}})$  for a Two-Tailed F-Test

$\frac{\nu_{\text{num}} \Rightarrow}{\downarrow \nu_{\text{denom}}}$	1	2	3	4	5	6	7	8	9	10	15	20	$\infty$
1	647.8	799.5	864.2	899.6	921.8	937.1	948.2	956.7	963.3	968.6	984.9	993.1	1018
2	38.51	39.00	39.17	39.25	39.30	39.33	39.36	39.37	39.39	39.40	39.43	39.45	39.50
3	17.44	16.04	15.44	15.10	14.88	14.73	14.62	14.54	14.47	14.42	14.25	14.17	13.90
4	12.22	10.65	9.979	9.605	9.364	9.197	9.074	8.980	8.905	8.844	8.657	8.560	8.257
5	10.01	8.434	7.764	7.388	7.146	6.978	6.853	6.757	6.681	6.619	6.428	6.329	6.015
6	8.813	7.260	6.599	6.227	5.988	5.820	5.695	5.600	5.523	5.461	5.269	5.168	4.894
7	8.073	6.542	5.890	5.523	5.285	5.119	4.995	4.899	4.823	4.761	4.568	4.467	4.142
8	7.571	6.059	5.416	5.053	4.817	4.652	4.529	4.433	4.357	4.259	4.101	3.999	3.670
9	7.209	5.715	5.078	4.718	4.484	4.320	4.197	4.102	4.026	3.964	3.769	3.667	3.333
10	6.937	5.456	4.826	4.468	4.236	4.072	3.950	3.855	3.779	3.717	3.522	3.419	3.080
11	6.724	5.256	4.630	4.275	4.044	3.881	3.759	3.644	3.588	3.526	3.330	3.226	2.883
12	6.544	5.096	4.474	4.121	3.891	3.728	3.607	3.512	3.436	3.374	3.177	3.073	2.725
13	6.414	4.965	4.347	3.996	3.767	3.604	3.483	3.388	3.312	3.250	3.053	2.948	2.596
14	6.298	4.857	4.242	3.892	3.663	3.501	3.380	3.285	3.209	3.147	2.949	2.844	2.487
15	6.200	4.765	4.153	3.804	3.576	3.415	3.293	3.199	3.123	3.060	2.862	2.756	2.395
16	6.115	4.687	4.077	3.729	3.502	3.341	3.219	3.125	3.049	2.986	2.788	2.681	2.316
17	6.042	4.619	4.011	3.665	3.438	3.277	3.156	3.061	2.985	2.922	2.723	2.616	2.247
18	5.978	4.560	3.954	3.608	3.382	3.221	3.100	3.005	2.929	2.866	2.667	2.559	2.187
19	5.922	4.508	3.903	3.559	3.333	3.172	3.051	2.956	2.880	2.817	2.617	2.509	2.133
20	5.871	4.461	3.859	3.515	3.289	3.128	3.007	2.913	2.837	2.774	2.573	2.464	2.085
$\infty$	5.024	3.689	3.116	2.786	2.567	2.408	2.288	2.192	2.114	2.048	1.833	1.708	1.000

## Appendix 6: Critical Values for Dixon's Q-Test

The following table provides critical values for  $Q(\alpha, n)$ , where  $\alpha$  is the probability of incorrectly rejecting the suspected outlier and  $n$  is the number of samples in the data set. There are several versions of Dixon's Q-Test, each of which calculates a value for  $Q_{ij}$  where  $i$  is the number of suspected outliers on one end of the data set and  $j$  is the number of suspected outliers on the opposite end of the data set. The values given here are for  $Q_{10}$ , where

$$Q_{\text{exp}} = Q_{10} = \frac{|\text{outlier's value} - \text{nearest value}|}{\text{largest value} - \text{smallest value}}$$

The suspected outlier is rejected if  $Q_{\text{exp}}$  is greater than  $Q(\alpha, n)$ . For additional information consult Rorabacher, D. B. "Statistical Treatment for Rejection of Deviant Values: Critical Values of Dixon's 'Q' Parameter and Related Subrange Ratios at the 95% confidence Level," *Anal. Chem.* **1991**, *63*, 139–146.

### Critical Values for the Q-Test of a Single Outlier ( $Q_{10}$ )

$\alpha \Rightarrow$ $\downarrow n$	0.1	0.05	0.04	0.02	0.01
3	0.941	0.970	0.976	0.988	0.994
4	0.765	0.829	0.846	0.889	0.926
5	0.642	0.710	0.729	0.780	0.821
6	0.560	0.625	0.644	0.698	0.740
7	0.507	0.568	0.586	0.637	0.680
8	0.468	0.526	0.543	0.590	0.634
9	0.437	0.493	0.510	0.555	0.598
10	0.412	0.466	0.483	0.527	0.568

## Appendix 7: Critical Values for Grubb's Test

The following table provides critical values for  $G(\alpha, n)$ , where  $\alpha$  is the probability of incorrectly rejecting the suspected outlier and  $n$  is the number of samples in the data set. There are several versions of Grubb's Test, each of which calculates a value for  $G_{ij}$  where  $i$  is the number of suspected outliers on one end of the data set and  $j$  is the number of suspected outliers on the opposite end of the data set. The values given here are for  $G_{10}$ , where

$$G_{\text{exp}} = G_{10} = \frac{|X_{\text{out}} - \bar{X}|}{s}$$

The suspected outlier is rejected if  $G_{\text{exp}}$  is greater than  $G(\alpha, n)$ .

$G(\alpha, n)$  for Grubb's Test of a Single Outlier

$\alpha \Rightarrow$ $\Downarrow n$	0.05	0.01
3	1.155	1.155
4	1.481	1.496
5	1.715	1.764
6	1.887	1.973
7	2.202	2.139
8	2.126	2.274
9	2.215	2.387
10	2.290	2.482
11	2.355	2.564
12	2.412	2.636
13	2.462	2.699
14	2.507	2.755
15	2.549	2.755

## Appendix 8: Recommended Primary Standards

All compounds should be of the highest available purity. Metals should be cleaned with dilute acid to remove any surface impurities and rinsed with distilled water. Unless otherwise indicated, compounds should be dried to a constant weight at 110 °C. Most of these compounds are soluble in dilute acid (1:1 HCl or 1:1 HNO<sub>3</sub>), with gentle heating if necessary; some of the compounds are water soluble.

Element	Compound	FW (g/mol)	Comments
aluminum	Al metal	26.982	
antimony	Sb metal	121.760	
	KSbOC <sub>4</sub> H <sub>4</sub> O <sub>6</sub>	324.92	prepared by drying KSbC <sub>4</sub> H <sub>4</sub> O <sub>6</sub> •1/2H <sub>2</sub> O at 110 °C and storing in a desiccator
arsenic	As metal	74.922	
	As <sub>2</sub> O <sub>3</sub>	197.84	toxic
barium	BaCO <sub>3</sub>	197.84	dry at 200 °C for 4 h
bismuth	Bi metal	208.98	
boron	H <sub>3</sub> BO <sub>3</sub>	61.83	do not dry
bromine	KBr	119.01	
cadmium	Cd metal	112.411	
	CdO	128.40	
calcium	CaCO <sub>3</sub>	100.09	
cerium	Ce metal	140.116	
	(NH <sub>4</sub> ) <sub>2</sub> Ce(NO <sub>3</sub> ) <sub>4</sub>	548.23	
cesium	Cs <sub>2</sub> CO <sub>3</sub>	325.82	
	Cs <sub>2</sub> SO <sub>4</sub>	361.87	
chlorine	NaCl	58.44	
chromium	Cr metal	51.996	
	K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	294.19	
cobalt	Co metal	58.933	
copper	Cu metal	63.546	
	CuO	79.54	
fluorine	NaF	41.99	do not store solutions in glass containers
iodine	KI	166.00	
	KIO <sub>3</sub>	214.00	
iron	Fe metal	55.845	
lead	Pb metal	207.2	
lithium	Li <sub>2</sub> CO <sub>3</sub>	73.89	
magnesium	Mg metal	24.305	
manganese	Mn metal	54.938	

Element	Compound	FW (g/mol)	Comments
mercury	Hg metal	200.59	
molybdenum	Mo metal	95.94	
nickel	Ni metal	58.693	
phosphorous	$\text{KH}_2\text{PO}_4$	136.09	
	$\text{P}_2\text{O}_5$	141.94	
potassium	KCl	74.56	
	$\text{K}_2\text{CO}_3$	138.21	
	$\text{K}_2\text{Cr}_2\text{O}_7$	294.19	
	$\text{KHC}_8\text{H}_4\text{O}_2$	204.23	
silicon	Si metal	28.085	
	$\text{SiO}_2$	60.08	
silver	Ag metal	107.868	
	$\text{AgNO}_3$	169.87	
sodium	NaCl	58.44	
	$\text{Na}_2\text{CO}_3$	106.00	
	$\text{Na}_2\text{C}_2\text{O}_4$	134.00	
strontium	$\text{SrCO}_3$	147.63	
sulfur	elemental S	32.066	
	$\text{K}_2\text{SO}_4$	174.27	
	$\text{Na}_2\text{SO}_4$	142.04	
tin	Sn metal	118.710	
titanium	Ti metal	47.867	
tungsten	W metal	183.84	
uranium	U metal	238.029	
	$\text{U}_3\text{O}_8$	842.09	
vanadium	V metal	50.942	
zinc	Zn metal	81.37	

Sources: (a) Smith, B. W.; Parsons, M. L. *J. Chem. Educ.* **1973**, *50*, 679–681; (b) Moody, J. R.; Greenburg, P. R.; Pratt, K. W.; Rains, T. C. *Anal. Chem.* **1988**, *60*, 1203A–1218A.

## Appendix 9: Correcting Mass for the Buoyancy of Air

Calibrating a balance does not eliminate all sources of determinate error in the signal. Because of the buoyancy of air, an object always weighs less in air than it does in a vacuum. If there is a difference between the object's density and the density of the weights used to calibrate the balance, then we can make a correction for buoyancy.<sup>1</sup> An object's true weight in vacuo,  $W_v$ , is related to its weight in air,  $W_a$ , by the equation

$$W_v = W_a \times \left[ 1 + \left( \frac{1}{D_o} - \frac{1}{D_w} \right) \times 0.0012 \right] \quad \text{A9.1}$$

where  $D_o$  is the object's density,  $D_w$  is the density of the calibration weight, and 0.0012 is the density of air under normal laboratory conditions (all densities are in units of  $\text{g}/\text{cm}^3$ ). The greater the difference between  $D_o$  and  $D_w$  the more serious the error in the object's measured weight.

The buoyancy correction for a solid is small, and frequently ignored. It may be significant, however, for low density liquids and gases. This is particularly important when calibrating glassware. For example, we can calibrate a volumetric pipet by carefully filling the pipet with water to its calibration mark, dispensing the water into a tared beaker, and determining the water's mass. After correcting for the buoyancy of air, we use the water's density to calculate the volume dispensed by the pipet.

### Example

A 10-mL volumetric pipet was calibrated following the procedure just outlined, using a balance calibrated with brass weights having a density of  $8.40 \text{ g}/\text{cm}^3$ . At  $25^\circ\text{C}$  the pipet dispensed  $9.9736 \text{ g}$  of water. What is the actual volume dispensed by the pipet and what is the determinate error in this volume if we ignore the buoyancy correction? At  $25^\circ\text{C}$  the density of water is  $0.99705 \text{ g}/\text{cm}^3$ .

### SOLUTION

Using equation A9.1 the water's true weight is

$$W_v = 9.9736 \text{ g} \times \left[ 1 + \left( \frac{1}{0.99705} - \frac{1}{8.40} \right) \times 0.0012 \right] = 9.9842 \text{ g}$$

and the actual volume of water dispensed by the pipet is

$$\frac{9.9842 \text{ g}}{0.99705 \text{ g}/\text{cm}^3} = 10.014 \text{ cm}^3 = 10.014 \text{ mL}$$

If we ignore the buoyancy correction, then we report the pipet's volume as

$$\frac{9.9736 \text{ g}}{0.99705 \text{ g}/\text{cm}^3} = 10.003 \text{ cm}^3 = 10.003 \text{ mL}$$

introducing a negative determinate error of  $-0.11\%$ .

<sup>1</sup> Battino, R.; Williamson, A. G. *J. Chem. Educ.* **1984**, *61*, 51–52.

**PROBLEMS**

The following problems will help you in considering the effect of buoyancy on the measurement of mass. Answers, but not worked solutions, are available [here](#).

1. In calibrating a 10-mL pipet a measured volume of water was transferred to a tared flask and weighed, yielding a mass of 9.9814 grams. (a) Calculate, with and without correcting for buoyancy, the volume of water delivered by the pipet. Assume that the density of water is 0.99707 g/cm<sup>3</sup> and that the density of the weights is 8.40 g/cm<sup>3</sup>. (b) What are the absolute and relative errors introduced by failing to account for the effect of buoyancy? Is this a significant source of determinate error for the calibration of a pipet? Explain.
2. Repeat the questions in problem 1 for the case where a mass of 0.2500 g is measured for a solid that has a density of 2.50 g/cm<sup>3</sup>.
3. Is the failure to correct for buoyancy a constant or proportional source of determinate error?
4. What is the minimum density of a substance necessary to keep the buoyancy correction to less than 0.01% when using brass calibration weights with a density of 8.40 g/cm<sup>3</sup>?

## Appendix 10: Solubility Products

The following table provides  $pK_{sp}$  and  $K_{sp}$  values for selected compounds, organized by the anion. All values are from Martell, A. E.; Smith, R. M. *Critical Stability Constants*, Vol. 4. Plenum Press: New York, 1976. Unless otherwise stated, values are for 25 °C and zero ionic strength.

Bromide ( $Br^-$ )	$pK_{sp}$	$K_{sp}$
CuBr	8.3	$5. \times 10^{-9}$
AgBr	12.30	$5.0 \times 10^{-13}$
Hg <sub>2</sub> Br <sub>2</sub>	22.25	$5.6 \times 10^{-13}$
HgBr <sub>2</sub> ( $\mu = 0.5$ M)	18.9	$1.3 \times 10^{-19}$
PbBr <sub>2</sub> ( $\mu = 4.0$ M)	5.68	$2.1 \times 10^{-6}$

Carbonate ( $CO_3^{2-}$ )	$pK_{sp}$	$K_{sp}$
MgCO <sub>3</sub>	7.46	$3.5 \times 10^{-8}$
CaCO <sub>3</sub> (calcite)	8.35	$4.5 \times 10^{-9}$
CaCO <sub>3</sub> (aragonite)	8.22	$6.0 \times 10^{-9}$
SrCO <sub>3</sub>	9.03	$9.3 \times 10^{-10}$
BaCO <sub>3</sub>	8.30	$5.0 \times 10^{-9}$
MnCO <sub>3</sub>	9.30	$5.0 \times 10^{-10}$
FeCO <sub>3</sub>	10.68	$2.1 \times 10^{-11}$
CoCO <sub>3</sub>	9.98	$1.0 \times 10^{-10}$
NiCO <sub>3</sub>	6.87	$1.3 \times 10^{-7}$
Ag <sub>2</sub> CO <sub>3</sub>	11.09	$8.1 \times 10^{-12}$
Hg <sub>2</sub> CO <sub>3</sub>	16.05	$8.9 \times 10^{-17}$
ZnCO <sub>3</sub>	10.00	$1.0 \times 10^{-10}$
CdCO <sub>3</sub>	13.74	$1.8 \times 10^{-14}$
PbCO <sub>3</sub>	13.13	$7.4 \times 10^{-14}$

Chloride ( $Cl^-$ )	$pK_{sp}$	$K_{sp}$
CuCl	6.73	$1.9 \times 10^{-7}$
AgCl	9.74	$1.8 \times 10^{-10}$
Hg <sub>2</sub> Cl <sub>2</sub>	17.91	$1.2 \times 10^{-18}$
PbCl <sub>2</sub>	4.78	$2.0 \times 10^{-19}$

Chromate ( $CrO_4^{2-}$ )	$pK_{sp}$	$K_{sp}$
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BaCrO <sub>4</sub>	9.67	2.1 × 10 <sup>-10</sup>
CuCrO <sub>4</sub>	5.44	3.6 × 10 <sup>-6</sup>
Ag <sub>2</sub> CrO <sub>4</sub>	11.92	1.2 × 10 <sup>-12</sup>
Hg <sub>2</sub> CrO <sub>4</sub>	8.70	2.0 × 10 <sup>-9</sup>

Cyanide (CN <sup>-</sup> )	pK <sub>sp</sub>	K <sub>sp</sub>
AgCN	15.66	2.2 × 10 <sup>-16</sup>
Zn(CN) <sub>2</sub> (μ = 3.0 M)	15.5	3. × 10 <sup>-16</sup>
Hg <sub>2</sub> (CN) <sub>2</sub>	39.3	5. × 10 <sup>-40</sup>

Ferrocyanide [Fe(CN) <sub>6</sub> <sup>4-</sup> ]	pK <sub>sp</sub>	K <sub>sp</sub>
Zn <sub>2</sub> [Fe(CN) <sub>6</sub> ]	15.68	2.1 × 10 <sup>-16</sup>
Cd <sub>2</sub> [Fe(CN) <sub>6</sub> ]	17.38	4.2 × 10 <sup>-18</sup>
Pb <sub>2</sub> [Fe(CN) <sub>6</sub> ]	18.02	9.5 × 10 <sup>-19</sup>

Fluoride (F <sup>-</sup> )	pK <sub>sp</sub>	K <sub>sp</sub>
MgF <sub>2</sub>	8.18	6.6 × 10 <sup>-9</sup>
CaF <sub>2</sub>	10.41	3.9 × 10 <sup>-11</sup>
SrF <sub>2</sub>	8.54	2.9 × 10 <sup>-9</sup>
BaF <sub>2</sub>	5.76	1.7 × 10 <sup>-6</sup>
PbF <sub>2</sub>	7.44	3.6 × 10 <sup>-8</sup>

Hydroxide (OH <sup>-</sup> )	pK <sub>sp</sub>	K <sub>sp</sub>
Mg(OH) <sub>2</sub>	11.15	7.1 × 10 <sup>-12</sup>
Ca(OH) <sub>2</sub>	5.19	6.5 × 10 <sup>-6</sup>
Ba(OH) <sub>2</sub> •8H <sub>2</sub> O	3.6	3. × 10 <sup>-4</sup>
La(OH) <sub>3</sub>	20.7	2. × 10 <sup>-21</sup>
Mn(OH) <sub>2</sub>	12.8	1.6 × 10 <sup>-13</sup>
Fe(OH) <sub>2</sub>	15.1	8. × 10 <sup>-16</sup>
Co(OH) <sub>2</sub>	14.9	1.3 × 10 <sup>-15</sup>
Ni(OH) <sub>2</sub>	15.2	6. × 10 <sup>-16</sup>
Cu(OH) <sub>2</sub>	19.32	4.8 × 10 <sup>-20</sup>
Fe(OH) <sub>3</sub>	38.8	1.6 × 10 <sup>-39</sup>
Co(OH) <sub>3</sub> (T = 19 °C)	44.5	3. × 10 <sup>-45</sup>

$\text{Ag}_2\text{O} (+ \text{H}_2\text{O} \rightleftharpoons 2\text{Ag}^+ + 2\text{OH}^-)$	15.42	$3.8 \times 10^{-16}$
$\text{Cu}_2\text{O} (+ \text{H}_2\text{O} \rightleftharpoons 2\text{Cu}^+ + 2\text{OH}^-)$	29.4	$4. \times 10^{-30}$
$\text{Zn}(\text{OH})_2$ (amorphous)	15.52	$3.0 \times 10^{-16}$
$\text{Cd}(\text{OH})_2$ ( $\beta$ )	14.35	$4.5 \times 10^{-15}$
$\text{HgO}$ (red) ( $+ \text{H}_2\text{O} \rightleftharpoons \text{Hg}^{2+} + 2\text{OH}^-$ )	25.44	$3.6 \times 10^{-26}$
$\text{SnO} (+ \text{H}_2\text{O} \rightleftharpoons \text{Sn}^{2+} + 2\text{OH}^-)$	26.2	$6. \times 10^{-27}$
$\text{PbO}$ (yellow) ( $+ \text{H}_2\text{O} \rightleftharpoons \text{Pb}^{2+} + 2\text{OH}^-$ )	15.1	$8. \times 10^{-16}$
$\text{Al}(\text{OH})_3$ ( $\alpha$ )	33.5	$3. \times 10^{-34}$

Iodate ( $\text{IO}_3^-$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{Ca}(\text{IO}_3)_2$	6.15	$7.1 \times 10^{-7}$
$\text{Ba}(\text{IO}_3)_2$	8.81	$1.5 \times 10^{-9}$
$\text{AgIO}_3$	7.51	$3.1 \times 10^{-8}$
$\text{Hg}_2(\text{IO}_3)_2$	17.89	$1.3 \times 10^{-18}$
$\text{Zn}(\text{IO}_3)_2$	5.41	$3.9 \times 10^{-6}$
$\text{Cd}(\text{IO}_3)_2$	7.64	$2.3 \times 10^{-8}$
$\text{Pb}(\text{IO}_3)_2$	12.61	$2.5 \times 10^{-13}$

Iodide ( $\text{I}^-$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{AgI}$	16.08	$8.3 \times 10^{-17}$
$\text{Hg}_2\text{I}_2$	28.33	$4.7 \times 10^{-29}$
$\text{HgI}_2$ ( $\mu = 0.5 \text{ M}$ )	27.95	$1.1 \times 10^{-28}$
$\text{PbI}_2$	8.10	$7.9 \times 10^{-9}$

Oxalate ( $\text{C}_2\text{O}_4^{2-}$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{CaC}_2\text{O}_4$ ( $\mu = 0.1 \text{ M}$ , $T = 20^\circ\text{C}$ )	7.9	$1.3 \times 10^{-8}$
$\text{BaC}_2\text{O}_4$ ( $\mu = 0.1 \text{ M}$ , $T = 20^\circ\text{C}$ )	6.0	$1. \times 10^{-6}$
$\text{SrC}_2\text{O}_4$ ( $\mu = 0.1 \text{ M}$ , $T = 20^\circ\text{C}$ )	6.4	$4. \times 10^{-7}$

Phosphate ( $\text{PO}_4^{3-}$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$	36.0	$1. \times 10^{-36}$
$\text{Zn}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$	35.3	$5. \times 10^{-36}$
$\text{Ag}_3\text{PO}_4$	17.55	$2.8 \times 10^{-18}$
$\text{Pb}_3(\text{PO}_4)_2$ ( $T = 38^\circ\text{C}$ )	43.55	$3.0 \times 10^{-44}$

Sulfate ( $\text{SO}_4^{2-}$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{CaSO}_4$	4.62	$2.4 \times 10^{-5}$
$\text{SrSO}_4$	6.50	$3.2 \times 10^{-7}$
$\text{BaSO}_4$	9.96	$1.1 \times 10^{-10}$
$\text{Ag}_2\text{SO}_4$	4.83	$1.5 \times 10^{-5}$
$\text{Hg}_2\text{SO}_4$	6.13	$7.4 \times 10^{-7}$
$\text{PbSO}_4$	7.79	$1.6 \times 10^{-8}$

Sulfide ( $\text{S}^{2-}$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{MnS}$ (green)	13.5	$3. \times 10^{-14}$
$\text{FeS}$	18.1	$8. \times 10^{-19}$
$\text{CoS}$ ( $\beta$ )	25.6	$3. \times 10^{-26}$
$\text{NiS}$ ( $\gamma$ )	26.6	$3. \times 10^{-27}$
$\text{CuS}$	36.1	$8. \times 10^{-37}$
$\text{Cu}_2\text{S}$	48.5	$3. \times 10^{-49}$
$\text{Ag}_2\text{S}$	50.1	$8. \times 10^{-51}$
$\text{ZnS}$ ( $\alpha$ )	24.7	$2. \times 10^{-25}$
$\text{CdS}$	27.0	$1. \times 10^{-27}$
$\text{Hg}_2\text{S}$ (red)	53.3	$5. \times 10^{-54}$
$\text{PbS}$	27.5	$3. \times 10^{-28}$

Thiocyanate ( $\text{SCN}^-$ )	$\text{p}K_{\text{sp}}$	$K_{\text{sp}}$
$\text{CuSCN}$ ( $\mu = 5.0 \text{ M}$ )	13.40	$4.0 \times 10^{-14}$
$\text{AgSCN}$	11.97	$1.1 \times 10^{-12}$
$\text{Hg}_2(\text{SCN})_2$	19.52	$3.0 \times 10^{-20}$
$\text{Hg}(\text{SCN})_2$ ( $\mu = 1.0 \text{ M}$ )	19.56	$2.8 \times 10^{-20}$

# Appendix 11: Acid Dissociation Constants

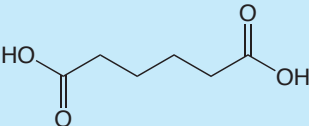
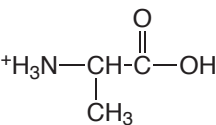
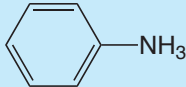
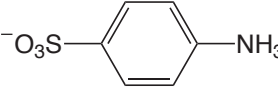
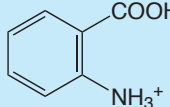
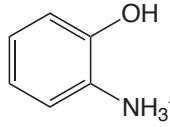
The following table provides  $pK_a$  and  $K_a$  values for selected weak acids. All values are from Martell, A. E.; Smith, R. M. *Critical Stability Constants*, Vols. 1–4. Plenum Press: New York, 1976. Unless otherwise stated, values are for 25 °C and zero ionic strength. Those values in brackets are considered less reliable.

Weak acids are arranged alphabetically by the names of the neutral compounds from which they are derived. In some cases—such as acetic acid—the compound is the weak acid. In other cases—such as for the ammonium ion—the neutral compound is the conjugate base. Chemical formulas or structural formulas are shown for the fully protonated weak acid. Successive acid dissociation constants are provided for polyprotic weak acids; where there is ambiguity, the specific acidic proton is identified.

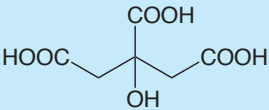
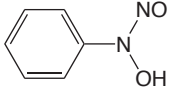
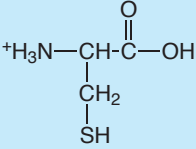
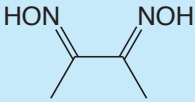
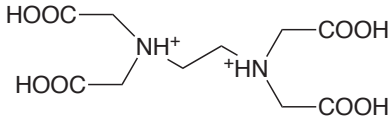
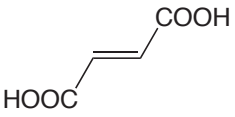
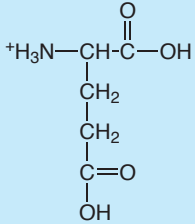
To find the  $K_b$  value for a conjugate weak base, recall that

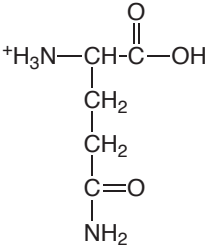
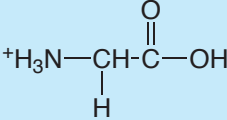
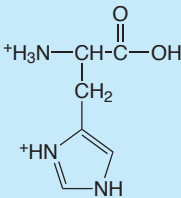
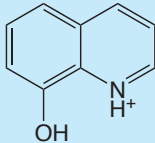
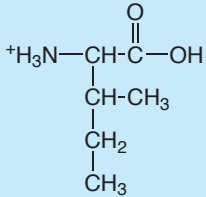
$$K_a \times K_b = K_w$$

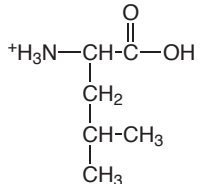
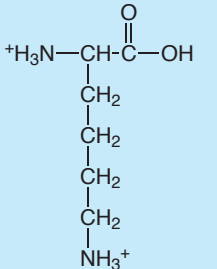

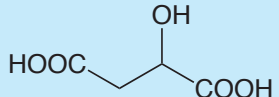
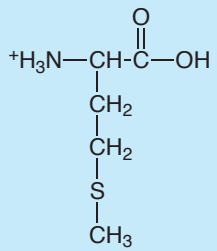
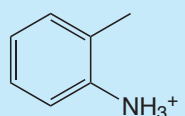
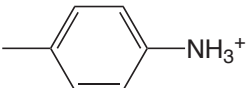
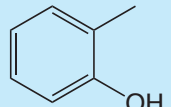
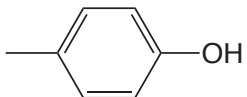
for a conjugate weak acid, HA, and its conjugate weak base, A<sup>−</sup>.

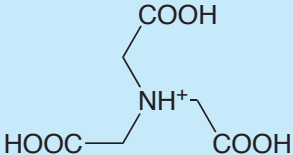
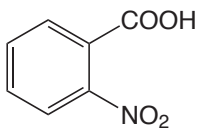
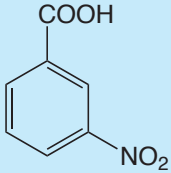
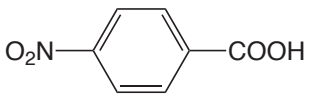
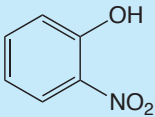
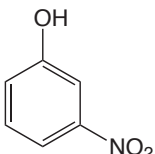
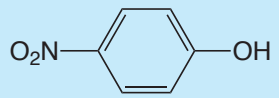
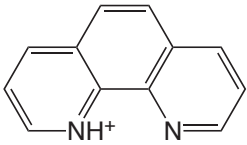
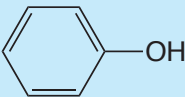
Compound	Conjugate Acid	$pK_a$	$K_a$
acetic acid	CH <sub>3</sub> COOH	4.757	$1.75 \times 10^{-5}$
adipic acid		4.42 5.42	$3.8 \times 10^{-5}$ $3.8 \times 10^{-6}$
alanine		2.348 (COOH) 9.867 (NH <sub>3</sub> )	$4.49 \times 10^{-3}$ $1.36 \times 10^{-10}$
aminobenzene		4.601	$2.51 \times 10^{-5}$
4-aminobenzene sulfonic acid		3.232	$5.86 \times 10^{-4}$
2-aminobenzoic acid		2.08 (COOH) 4.96 (NH <sub>3</sub> )	$8.3 \times 10^{-3}$ $1.1 \times 10^{-5}$
2-aminophenol ( $T=20^\circ\text{C}$ )		4.78 (NH <sub>3</sub> ) 9.97 (OH)	$1.7 \times 10^{-5}$ $1.05 \times 10^{-10}$
ammonia	NH <sub>4</sub> <sup>+</sup>	9.244	$5.70 \times 10^{-10}$

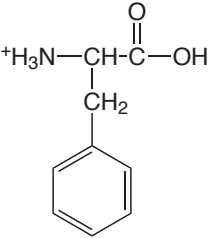
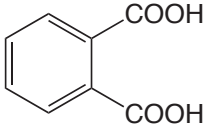
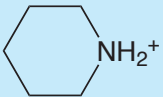
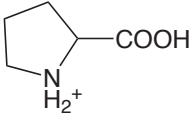
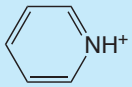
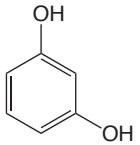
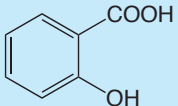
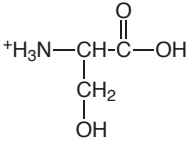
Compound	Conjugate Acid	$pK_a$	$K_a$
arginine		1.823 (COOH) 8.991 (NH <sub>3</sub> ) [12.48] (NH <sub>2</sub> )	$1.50 \times 10^{-2}$ $1.02 \times 10^{-9}$ [ $3.3 \times 10^{-13}$ ]
arsenic acid	H <sub>3</sub> AsO <sub>4</sub>	2.24 6.96 11.50	$5.8 \times 10^{-3}$ $1.1 \times 10^{-7}$ $3.2 \times 10^{-12}$
asparagine ( $\mu = 0.1$ M)		2.14 (COOH) 8.72 (NH <sub>3</sub> )	$7.2 \times 10^{-3}$ $1.9 \times 10^{-9}$
aspartic acid		1.990 ( $\alpha$ -COOH) 3.900 ( $\beta$ -COOH) 10.002 (NH <sub>3</sub> )	$1.02 \times 10^{-2}$ $1.26 \times 10^{-4}$ $9.95 \times 10^{-11}$
benzoic acid		4.202	$6.28 \times 10^{-5}$
benzylamine		9.35	$4.5 \times 10^{-10}$
boric acid ( $pK_{a2}, pK_{a3}: T = 20^\circ\text{C}$ )	H <sub>3</sub> BO <sub>3</sub>	9.236 [12.74] [13.80]	$5.81 \times 10^{-10}$ [ $1.82 \times 10^{-13}$ ] [ $1.58 \times 10^{-14}$ ]
carbonic acid	H <sub>2</sub> CO <sub>3</sub>	6.352 10.329	$4.45 \times 10^{-7}$ $4.69 \times 10^{-11}$
catechol		9.40 12.8	$4.0 \times 10^{-10}$ $1.6 \times 10^{-13}$
chloroacetic acid	ClCH <sub>2</sub> COOH	2.865	$1.36 \times 10^{-3}$
chromic acid ( $pK_{a1}: T = 20^\circ\text{C}$ )	H <sub>2</sub> CrO <sub>4</sub>	-0.2 6.51	1.6 $3.1 \times 10^{-7}$

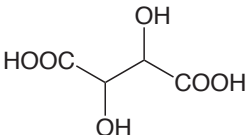
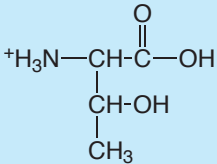
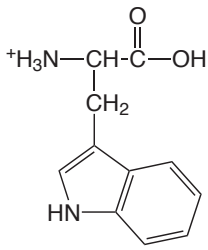
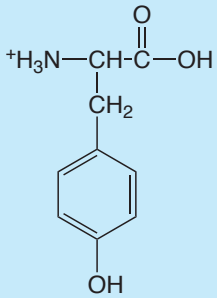
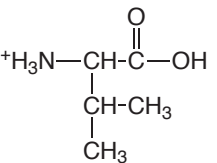
Compound	Conjugate Acid	pK <sub>a</sub>	K <sub>a</sub>
citric acid		3.128 (COOH)	$7.45 \times 10^{-4}$
		4.761 (COOH)	$1.73 \times 10^{-5}$
		6.396 (COOH)	$4.02 \times 10^{-7}$
cupferron ( $\mu = 0.1$ M)		4.16	$6.9 \times 10^{-5}$
cysteine		[1.71] (COOH)	$[1.9 \times 10^{-2}]$
		8.36 (SH)	$4.4 \times 10^{-9}$
		10.77 (NH <sub>3</sub> )	$1.7 \times 10^{-11}$
dichloroacetic acid	Cl <sub>2</sub> CHCOOH	1.30	$5.0 \times 10^{-2}$
diethylamine	(CH <sub>3</sub> CH <sub>2</sub> ) <sub>2</sub> NH <sub>2</sub> <sup>+</sup>	10.933	$1.17 \times 10^{-11}$
dimethylamine	(CH <sub>3</sub> ) <sub>2</sub> NH <sub>2</sub> <sup>+</sup>	10.774	$1.68 \times 10^{-11}$
dimethylglyoxime		10.66	$2.2 \times 10^{-11}$
		12.0	$1. \times 10^{-12}$
ethylamine	CH <sub>3</sub> CH <sub>2</sub> NH <sub>3</sub> <sup>+</sup>	10.636	$2.31 \times 10^{-11}$
ethylenediamine	<sup>+</sup> H <sub>3</sub> NCH <sub>2</sub> CH <sub>2</sub> NH <sub>3</sub> <sup>+</sup>	6.848	$1.42 \times 10^{-7}$
		9.928	$1.18 \times 10^{-10}$
ethylenediaminetetraacetic acid (EDTA) ( $\mu = 0.1$ M)		0.0 (COOH)	1.0
		1.5 (COOH)	$3.2 \times 10^{-2}$
		2.0 (COOH)	$1.0 \times 10^{-2}$
		2.66 (COOH)	$2.2 \times 10^{-3}$
		6.16 (NH)	$6.9 \times 10^{-7}$
		10.24 (NH)	$5.8 \times 10^{-11}$
formic acid	HCOOH	3.745	$1.80 \times 10^{-4}$
fumaric acid		3.053	$8.85 \times 10^{-4}$
		4.494	$3.21 \times 10^{-5}$
glutamic acid		2.33 ( $\alpha$ -COOH)	$5.9 \times 10^{-3}$
		4.42 ( $\lambda$ -COOH)	$3.8 \times 10^{-5}$
		9.95 (NH <sub>3</sub> )	$1.12 \times 10^{-10}$

Compound	Conjugate Acid	pK <sub>a</sub>	K <sub>a</sub>
glutamine (μ = 0.1 M)		2.17 (COOH) 9.01 (NH <sub>3</sub> )	6.8 × 10 <sup>-3</sup> 9.8 × 10 <sup>-10</sup>
glycine +H <sub>3</sub> NCH <sub>2</sub> COOH		2.350 (COOH) 9.778 (NH <sub>3</sub> )	4.47 × 10 <sup>-3</sup> 1.67 × 10 <sup>-10</sup>
glycolic acid	HOOCH <sub>2</sub> COOH	3.831 (COOH)	1.48 × 10 <sup>-4</sup>
histidine (μ = 0.1 M)		1.7 (COOH) 6.02 (NH) 9.08 (NH <sub>3</sub> )	2. × 10 <sup>-2</sup> 9.5 × 10 <sup>-7</sup> 8.3 × 10 <sup>-10</sup>
hydrogen cyanide	HCN	9.21	6.2 × 10 <sup>-10</sup>
hydrogen fluoride	HF	3.17	6.8 × 10 <sup>-4</sup>
hydrogen peroxide	H <sub>2</sub> O <sub>2</sub>	11.65	2.2 × 10 <sup>-12</sup>
hydrogen sulfide	H <sub>2</sub> S	7.02 13.9	9.5 × 10 <sup>-8</sup> 1.3 × 10 <sup>-14</sup>
hydrogen thiocyanate	HSCN	0.9	1.3 × 10 <sup>-1</sup>
8-hydroxyquinoline		4.91 (NH) 9.81 (OH)	1.2 × 10 <sup>-5</sup> 1.6 × 10 <sup>-10</sup>
hydroxylamine	HONH <sub>3</sub> <sup>+</sup>	5.96	1.1 × 10 <sup>-6</sup>
hypobromous acid	HOBr	8.63	2.3 × 10 <sup>-9</sup>
hypochlorous acid	HOCl	7.53	3.0 × 10 <sup>-8</sup>
hypoiodous acid	HOI	10.64	2.3 × 10 <sup>-11</sup>
iodic acid	HIO <sub>3</sub>	0.77	1.7 × 10 <sup>-1</sup>
isoleucine		2.319 (COOH) 9.754 (NH <sub>3</sub> )	4.80 × 10 <sup>-3</sup> 1.76 × 10 <sup>-10</sup>

Compound	Conjugate Acid	pK <sub>a</sub>	K <sub>a</sub>
leucine		2.329 (COOH) 9.747 (NH <sub>3</sub> )	4.69 × 10 <sup>-3</sup> 1.79 × 10 <sup>-10</sup>
lysine (μ = 0.1 M)		2.04 (COOH) 9.08 (α-NH <sub>3</sub> ) 10.69 (ε-NH <sub>3</sub> )	9.1 × 10 <sup>-3</sup> 8.3 × 10 <sup>-10</sup> 2.0 × 10 <sup>-11</sup>
maleic acid		1.910 6.332	9.1 × 10 <sup>-3</sup> 9.1 × 10 <sup>-3</sup>
malic acid		3.459 (COOH) 5.097 (COOH)	9.1 × 10 <sup>-3</sup> 9.1 × 10 <sup>-3</sup>
malonic acid	HOOCCH <sub>2</sub> COOH	2.847 5.696	9.1 × 10 <sup>-3</sup> 9.1 × 10 <sup>-3</sup>
methionine (μ = 0.1 M)		2.20 (COOH) 9.05 (NH <sub>3</sub> )	9.1 × 10 <sup>-3</sup> 9.1 × 10 <sup>-3</sup>
methylamine	CH <sub>3</sub> NH <sub>3</sub> <sup>+</sup>	10.64	9.1 × 10 <sup>-3</sup>
2-methylaniline		4.447	9.1 × 10 <sup>-3</sup>
4-methylaniline		5.084	9.1 × 10 <sup>-3</sup>
2-methylphenol		10.28	9.1 × 10 <sup>-3</sup>
4-methylphenol		10.26	9.1 × 10 <sup>-3</sup>

Compound	Conjugate Acid	$pK_a$	$K_a$
nitrilotriacetic acid ( $T=20^\circ\text{C}$ ) ( $pK_{a1}; \mu = 0.1 \text{ m}$ )		1.1 (COOH) 1.650 (COOH) 2.940 (COOH) 10.334 (NH <sub>3</sub> )	$9.1 \times 10^{-3}$ $9.1 \times 10^{-3}$ $9.1 \times 10^{-3}$ $9.1 \times 10^{-3}$
2-nitrobenzoic acid		2.179	$9.1 \times 10^{-3}$
3-nitrobenzoic acid		3.449	$9.1 \times 10^{-3}$
4-nitrobenzoic acid		3.442	$3.61 \times 10^{-4}$
2-nitrophenol		7.21	$6.2 \times 10^{-8}$
3-nitrophenol		8.39	$4.1 \times 10^{-9}$
4-nitrophenol		7.15	$7.1 \times 10^{-8}$
nitrous acid	HNO <sub>2</sub>	3.15	$7.1 \times 10^{-4}$
oxalic acid	H <sub>2</sub> C <sub>2</sub> O <sub>4</sub>	1.252 4.266	$5.60 \times 10^{-2}$ $5.42 \times 10^{-5}$
1,10-phenanthroline		4.86	$1.38 \times 10^{-5}$
phenol		9.98	$1.05 \times 10^{-10}$

Compound	Conjugate Acid	pK <sub>a</sub>	K <sub>a</sub>
phenylalanine		2.20 (COOH) 9.31 (NH <sub>3</sub> )	6.3 × 10 <sup>-3</sup> 4.9 × 10 <sup>-10</sup>
phosphoric acid	H <sub>3</sub> PO <sub>4</sub>	2.148 7.199 12.35	7.11 × 10 <sup>-3</sup> 6.32 × 10 <sup>-8</sup> 4.5 × 10 <sup>-13</sup>
phthalic acid		2.950 5.408	1.12 × 10 <sup>-3</sup> 3.91 × 10 <sup>-6</sup>
piperidine		11.123	7.53 × 10 <sup>-12</sup>
proline		1.952 (COOH) 10.640 (NH)	1.12 × 10 <sup>-2</sup> 2.29 × 10 <sup>-11</sup>
propanoic acid	CH <sub>3</sub> CH <sub>2</sub> COOH	4.874	1.34 × 10 <sup>-5</sup>
propylamine	CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> NH <sub>3</sub> <sup>+</sup>	10.566	2.72 × 10 <sup>-11</sup>
pyridine		5.229	5.90 × 10 <sup>-6</sup>
resorcinol		9.30 11.06	5.0 × 10 <sup>-10</sup> 8.7 × 10 <sup>-12</sup>
salicylic acid		2.97 (COOH) 13.74 (OH)	1.1 × 10 <sup>-3</sup> 1.8 × 10 <sup>-14</sup>
serine		2.187 (COOH) 9.209 (NH <sub>3</sub> )	6.50 × 10 <sup>-3</sup> 6.18 × 10 <sup>-10</sup>
succinic acid	HOOC-CH <sub>2</sub> -CH <sub>2</sub> -COOH	4.207 5.636	6.21 × 10 <sup>-5</sup> 2.31 × 10 <sup>-6</sup>
sulfuric acid	H <sub>2</sub> SO <sub>4</sub>	strong 1.99	— 1.0 × 10 <sup>-2</sup>

Compound	Conjugate Acid	p <i>K</i> <sub>a</sub>	<i>K</i> <sub>a</sub>
sulfurous acid	H <sub>2</sub> SO <sub>3</sub>	1.91 7.18	1.2 × 10 <sup>-2</sup> 6.6 × 10 <sup>-8</sup>
D-tartaric acid		3.036 (COOH) 4.366 (COOH)	9.20 × 10 <sup>-4</sup> 4.31 × 10 <sup>-5</sup>
threonine		2.088 (COOH) 9.100 (NH <sub>3</sub> )	8.17 × 10 <sup>-3</sup> 7.94 × 10 <sup>-10</sup>
thiosulfuric acid	H <sub>2</sub> S <sub>2</sub> O <sub>3</sub>	0.6 1.6	3. × 10 <sup>-1</sup> 3. × 10 <sup>-2</sup>
trichloroacetic acid (μ = 0.1 M)	Cl <sub>3</sub> CCOOH	0.66	2.2 × 10 <sup>-1</sup>
triethanolamine	(HOCH <sub>2</sub> CH <sub>2</sub> ) <sub>3</sub> NH <sup>+</sup>	7.762	1.73 × 10 <sup>-8</sup>
triethylamine	(CH <sub>3</sub> CH <sub>2</sub> ) <sub>3</sub> NH <sup>+</sup>	10.715	1.93 × 10 <sup>-11</sup>
trimethylamine	(CH <sub>3</sub> ) <sub>3</sub> NH <sup>+</sup>	9.800	1.58 × 10 <sup>-10</sup>
tris(hydroxymethyl)amino methane (TRIS or THAM)	(HOCH <sub>2</sub> ) <sub>3</sub> CNH <sub>3</sub> <sup>+</sup>	8.075	8.41 × 10 <sup>-9</sup>
tryptophan (μ = 0.1 M)		2.35 (COOH) 9.33 (NH <sub>3</sub> )	4.5 × 10 <sup>-3</sup> 4.7 × 10 <sup>-10</sup>
tyrosine (p <i>K</i> <sub>a1</sub> : μ = 0.1 M)		2.17 (COOH) 9.19 (NH <sub>3</sub> ) 10.47 (OH)	6.8 × 10 <sup>-3</sup> 6.5 × 10 <sup>-10</sup> 3.4 × 10 <sup>-11</sup>
valine		2.286 (COOH) 9.718 (NH <sub>3</sub> )	5.18 × 10 <sup>-3</sup> 1.91 × 10 <sup>-10</sup>

## Appendix 12: Formation Constants


The following table provides  $K_i$  and  $\beta_i$  values for selected metal–ligand complexes, arranged by the ligand. All values are from Martell, A. E.; Smith, R. M. *Critical Stability Constants*, Vols. 1–4. Plenum Press: New York, 1976. Unless otherwise stated, values are for 25 °C and zero ionic strength. Those values in brackets are considered less reliable.

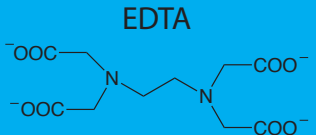
Acetate $\text{CH}_3\text{COO}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Mg}^{2+}$	1.27					
$\text{Ca}^{2+}$	1.18					
$\text{Ba}^{2+}$	1.07					
$\text{Mn}^{2+}$	1.40					
$\text{Fe}^{2+}$	1.40					
$\text{Co}^{2+}$	1.46					
$\text{Ni}^{2+}$	1.43					
$\text{Cu}^{2+}$	2.22	1.41				
$\text{Ag}^{2+}$	0.73	−0.09				
$\text{Zn}^{2+}$	1.57					
$\text{Cd}^{2+}$	1.93	1.22	−0.89			
$\text{Pb}^{2+}$	2.68	1.40				

Ammonia $\text{NH}_3$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Ag}^+$	3.31	3.91				
$\text{Co}^{2+}$ ( $T=20^\circ\text{C}$ )	1.99	1.51	0.93	0.64	0.06	−0.73
$\text{Ni}^{2+}$	2.72	2.17	1.66	1.12	0.67	−0.03
$\text{Cu}^{2+}$	4.04	3.43	2.80	1.48		
$\text{Zn}^{2+}$	2.21	2.29	2.36	2.03		
$\text{Cd}^{2+}$	2.55	2.01	1.34	0.84		

Chloride $\text{Cl}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Cu}^{2+}$	0.40					
$\text{Fe}^{3+}$	1.48	0.65				
$\text{Ag}^+$ ( $\mu = 5.0 \text{ M}$ )	3.70	1.92	0.78	−0.3		
$\text{Zn}^{2+}$	0.43	0.18	−0.11	−0.3		
$\text{Cd}^{2+}$	1.98	1.62	−0.2	−0.7		
$\text{Pb}^{2+}$	1.59	0.21	−0.1	−0.3		

Cyanide CN <sup>-</sup>	log K <sub>1</sub>	log K <sub>2</sub>	log K <sub>3</sub>	log K <sub>4</sub>	log K <sub>5</sub>	log K <sub>6</sub>
Fe <sup>2+</sup>						35.4 (β <sub>6</sub> )
Fe <sup>3+</sup>						43.6 (β <sub>6</sub> )
Ag <sup>+</sup>		20.48 β <sub>2</sub>	0.92			
Zn <sup>2+</sup>		11.07 β <sub>2</sub>	4.98	3.57		
Cd <sup>2+</sup>	6.01	5.11	4.53	2.27		
Hg <sup>2+</sup>	17.00	15.75	3.56	2.66		
Ni <sup>2+</sup>					30.22 (β <sub>4</sub> )	

Ethylenediamine 	log K <sub>1</sub>	log K <sub>2</sub>	log K <sub>3</sub>	log K <sub>4</sub>	log K <sub>5</sub>	log K <sub>6</sub>
Ni <sup>2+</sup>	7.38	6.18	4.11			
Cu <sup>2+</sup>	10.48	9.07				
Ag <sup>+</sup> (T = 20 °C, μ = 0.1 M)	4.700	3.00				
Zn <sup>2+</sup>	5.66	4.98	3.25			
Cd <sup>2+</sup>	5.41	4.50	2.78			

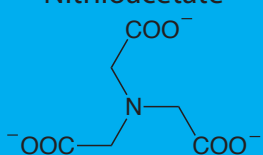
EDTA 	log K <sub>1</sub>	log K <sub>2</sub>	log K <sub>3</sub>	log K <sub>4</sub>	log K <sub>5</sub>	log K <sub>6</sub>
Mg <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	8.79					
Ca <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	10.69					
Ba <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	7.86					
Bi <sup>3+</sup> (T = 20 °C, μ = 0.1 M)	27.8					
Co <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	16.31					
Ni <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	18.62					
Cu <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	18.80					
Cr <sup>3+</sup> (T = 20 °C, μ = 0.1 M)	[23.4]					
Fe <sup>3+</sup> (T = 20 °C, μ = 0.1 M)	25.1					
Ag <sup>+</sup> (T = 20 °C, μ = 0.1 M)	7.32					
Zn <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	16.50					
Cd <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	16.46					
Hg <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	21.7					
Pb <sup>2+</sup> (T = 20 °C, μ = 0.1 M)	18.04					

$\text{Al}^{3+}$  ( $T=20^\circ\text{C}$ ,  $\mu=0.1\text{ M}$ ) 16.3

Fluoride						
$\text{F}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Al}^{3+}$ ( $\mu=0.5\text{ M}$ )	6.11	5.01	3.88	3.0	1.4	0.4

Hydroxide						
$\text{OH}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Al}^{3+}$	9.01	[9.69]	[8.3]	6.0		
$\text{Co}^{2+}$	4.3	4.1	1.3	0.5		
$\text{Fe}^{2+}$	4.5	[2.9]	2.6	-0.4		
$\text{Fe}^{3+}$	11.81	10.5	12.1			
$\text{Ni}^{2+}$	4.1	3.9	3.			
$\text{Pb}^{2+}$	6.3	4.6	3.0			
$\text{Zn}^{2+}$	5.0	[6.1]	2.5	[1.2]		

Iodide						
$\text{I}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Ag}^+$ ( $T=18^\circ\text{C}$ )	6.58	[5.12]	[1.4]			
$\text{Cd}^{2+}$	2.28	1.64	1.08	1.0		
$\text{Pb}^{2+}$	1.92	1.28	0.7	0.6		

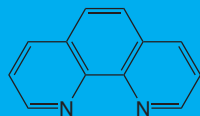
Nitriloacetate						
	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Mg}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	5.41					
$\text{Ca}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	6.41					
$\text{Ba}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	4.82					
$\text{Mn}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	7.44					
$\text{Fe}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	8.33					
$\text{Co}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	10.38					
$\text{Ni}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	11.53					
$\text{Cu}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	12.96					
$\text{Fe}^{3+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	15.9					
$\text{Zn}^{2+}$ ( $T=20^\circ\text{C}$ , $\mu=0.1\text{ M}$ )	10.67					

$\text{Cd}^{2+}$  ( $T=20^\circ\text{C}$ ,  $\mu=0.1\text{ M}$ ) 9.83

$\text{Pb}^{2+}$  ( $T=20^\circ\text{C}$ ,  $\mu=0.1\text{ M}$ ) 11.39

Oxalate $\text{C}_2\text{O}_4^{2-}$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Ca}^{2+}$ ( $\mu=1\text{ M}$ )	1.66	1.03				
$\text{Fe}^{2+}$ ( $\mu=1\text{ M}$ )	3.05	2.10				
$\text{Co}^{2+}$	4.72	2.28				
$\text{Ni}^{2+}$	5.16					
$\text{Cu}^{2+}$	6.23	4.04				
$\text{Fe}^{3+}$ ( $\mu=0.5\text{ M}$ )	7.53	6.11	4.85			
$\text{Zn}^{2+}$	4.87	2.78				

### 1,10-Phenanthroline



	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Fe}^{2+}$			20.7 ( $\beta_3$ )			
$\text{Mn}^{2+}$ ( $\mu=0.1\text{ M}$ )	4.0	3.3	3.0			
$\text{Co}^{2+}$ ( $\mu=0.1\text{ M}$ )	7.08	6.64	6.08			
$\text{Ni}^{2+}$	8.6	8.1	7.6			
$\text{Fe}^{3+}$			13.8 ( $\beta_3$ )			
$\text{Ag}^+$ ( $\mu=0.1\text{ M}$ )	5.02	7.04				
$\text{Zn}^{2+}$	6.2	[5.9]	[5.2]			

Thiosulfate $\text{S}_2\text{O}_3^{2-}$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Ag}^+$ ( $T=20^\circ\text{C}$ )	8.82	4.85	0.53			

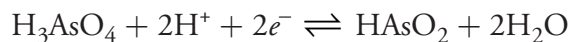
Thiocyanate $\text{SCN}^-$	$\log K_1$	$\log K_2$	$\log K_3$	$\log K_4$	$\log K_5$	$\log K_6$
$\text{Mn}^{2+}$	1.23					
$\text{Fe}^{2+}$	1.31					
$\text{Co}^{2+}$	1.72					
$\text{Ni}^{2+}$	1.76					
$\text{Cu}^{2+}$	2.33					
$\text{Fe}^{3+}$	3.02					

Ag <sup>+</sup>	4.8	3.43	1.27	0.2
Zn <sup>2+</sup>	1.33	0.58	0.09	-0.4
Cd <sup>2+</sup>	1.89	0.89	0.02	-0.5
Hg <sup>2+</sup>		17.26 ( $\beta_2$ )	2.71	1.83

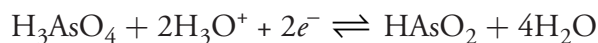
## Appendix 13: Standard Reduction Potentials

The following table provides  $E^\circ$  and  $E^{\circ'}$  values for selected reduction reactions, organized by element. Values are compiled from the following sources: Bard, A. J.; Parsons, B.; Jordon, J., eds. *Standard Potentials in Aqueous Solutions*, Dekker: New York, 1985; Milazzo, G.; Caroli, S.; Sharma, V. K. *Tables of Standard Electrode Potentials*, Wiley: London, 1978; Swift, E. H.; Butler, E. A. *Quantitative Measurements and Chemical Equilibria*, Freeman: New York, 1972.

Solid, gas, and liquid species are identified; all other species are aqueous. Reduction reactions in acidic solution are written using  $H^+$  in place of  $H_3O^+$ . You may rewrite a reaction by replacing  $H^+$  with  $H_3O^+$  and adding to the opposite side of the reaction one molecule of  $H_2O$  per  $H^+$ ; thus



becomes



Conditions for formal potentials ( $E^{\circ'}$ ) are listed next to the potential.

## Appendix 14: Random Number Table

The following table provides a list of random numbers in which the digits 0 through 9 appear with approximately equal frequency. Numbers are arranged in groups of five to make the table easier to view. This arrangement is arbitrary, and you can treat the table as a sequence of random individual digits (1, 2, 1, 3, 7, 4...going down the first column of digits on the left side of the table), as a sequence of three digit numbers (111, 212, 104, 367, 739... using the first three columns of digits on the left side of the table), or in any other similar manner.

Let's use the table to pick 10 random numbers between 1 and 50. To do so, we choose a random starting point, perhaps by dropping a pencil onto the table. For this exercise, we will assume that the starting point is the fifth row of the third column, or 12032. Because the numbers must be between 1 and 50, we will use the last two digits, ignoring all two-digit numbers less than 01 or greater than 50, and rejecting any duplicates. Proceeding down the third column, and moving to the top of the fourth column when necessary, gives the following 10 random numbers: 32, 01, 05, 16, 15, 38, 24, 10, 26, 14.

These random numbers (1000 total digits) are a small subset of values from the publication *Million Random Digits* (Rand Corporation, 2001) are used with permission. Information about the publication, and a link to a text file containing the million random digits is available at [http://www.rand.org/pubs/monograph\\_reports/MR1418/](http://www.rand.org/pubs/monograph_reports/MR1418/).

11164	36318	75061	37674	26320	75100	10431	20418	19228	91792
21215	91791	76831	58678	87054	31687	93205	43685	19732	08468
10438	44482	66558	37649	08882	90870	12462	41810	01806	02977
36792	26236	33266	66583	60881	97395	20461	36742	02852	50564
73944	04773	12032	51414	82384	38370	00249	80709	72605	67497
49563	12872	14063	93104	78483	72717	68714	18048	25005	04151
64208	48237	41701	73117	33242	42314	83049	21933	92813	04763
51486	72875	38605	29341	80749	80151	33835	52602	79147	08868
99756	26360	64516	17971	48478	09610	04638	17141	09227	10606
71325	55217	13015	72907	00431	45117	33827	92873	02953	85474
65285	97198	12138	53010	95601	15838	16805	61004	43516	17020
17264	57327	38224	29301	31381	38109	34976	65692	98566	29550
95639	99754	31199	92558	68368	04985	51092	37780	40261	14479
61555	76404	86210	11808	12841	45147	97438	60022	12645	62000
78137	98768	04689	87130	79225	08153	84967	64539	79493	74917
62490	99215	84987	28759	19177	14733	24550	28067	68894	38490
24216	63444	21283	07044	92729	37284	13211	37485	10415	36457
16975	95428	33226	55903	31605	43817	22250	03918	46999	98501
59138	39542	71168	57609	91510	77904	74244	50940	31553	62562
29478	59652	50414	31966	87912	87514	12944	49862	96566	48825

## Appendix 15: Polarographic Half-Wave Potentials

The following table provides a list of random numbers in which the digits 0 through 9 appear with approximately equal frequency. Numbers are arranged in groups of five to make the table easier to view. This arrangement is arbitrary, and you can treat the table as a sequence of random individual digits (1, 2, 1, 3, 7, 4...going down the first column of digits on the left side of the table), as a sequence of three digit numbers (111, 212, 104, 367, 739... using the first three columns of digits on the left side of the table), or in any other similar manner.

## Appendix 16: Countercurrent Separations

The following table provides a list of random numbers in which the digits 0 through 9 appear with approximately equal frequency. Numbers are arranged in groups of five to make the table easier to view. This arrangement is arbitrary, and you can treat the table as a sequence of random individual digits (1, 2, 1, 3, 7, 4...going down the first column of digits on the left side of the table), as a sequence of three digit numbers (111, 212, 104, 367, 739... using the first three columns of digits on the left side of the table), or in any other similar manner.

## Appendix 17: Review of Chemical Kinetics

The following table provides a list of random numbers in which the digits 0 through 9 appear with approximately equal frequency. Numbers are arranged in groups of five to make the table easier to view. This arrangement is arbitrary, and you can treat the table as a sequence of random individual digits (1, 2, 1, 3, 7, 4...going down the first column of digits on the left side of the table), as a sequence of three digit numbers (111, 212, 104, 367, 739... using the first three columns of digits on the left side of the table), or in any other similar manner.