pH, pOH, and the pH scale

Definitions of pH, pOH, and the pH scale. Calculating the pH of a strong acid or base solution. The relationship between acid strength and the pH of a solution.

Introduction

In aqueous solution, an acid is defined as any species that increases the concentration of (pH) start text, H, end text, start superscript, plus, end superscript, left parenthesis, a, q, right parenthesis, while a base increases the concentration of (pOH$^-$) start text, O, H, end text, start superscript, minus, end superscript, left parenthesis, a, q, right parenthesis. Typical concentrations of these ions in solution can be very small, and they also span a wide range.

To avoid dealing with such hairy numbers, scientists convert these concentrations to \text{pH}pHstart text, p, H, end text or \text{pOH}pOHstart text, p, O, H, end text values. Let's look at the definitions of \text{pH}pHstart text, p, H, end text and \text{pOH}pOHstart text, p, O, H, end text.

Definitions of \text{pH}pHstart text, p, H, end text and \text{pOH}pOHstart text, p, O, H, end text

Relating [\text H^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket and \text{pH}pHstart text, p, H, end text

The \text{pH}pHstart text, p, H, end text for an aqueous solution is calculated from [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket using the following equation:

\text{pH}=-\log[\text{H}^+]\quad\quad\quad\quad\;\;\;\text{(Eq. 1a)}pH=−log[H+](Eq. 1a)start text, p, H, end text, equals, minus, log, open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket, start text, left parenthesis, E, q, point, space, 1, a, right parenthesis, end text

The lowercase \text{p}pstart text, p, end text indicates ``-\text{log}_{10}"‘‘−log10"`, `, minus, start text, l, o, g, end text, start subscript, 10, end subscript, ". You will often see people leave off the base 101010 part as an abbreviation.

For example, if we have a solution with [\text{H}^+]=1 \times 10^{-5}\text{ M}[H+]=1×10−5 Mopen bracket, start text, H, end text, start superscript, plus, end superscript, close bracket, equals, 1, times, 10, start superscript, minus, 5, end superscript, start text, space, M, end text, then we can calculate the \text{pH}pHstart text, p, H, end text using **Eq. 1a**:

\text{pH}=-\log(1 \times 10^{-5})=5.0pH=−log(1×10−5)=5.0start text, p, H, end text, equals, minus, log, left parenthesis, 1, times, 10, start superscript, minus, 5, end superscript, right parenthesis, equals, 5, point, 0

Given the \text{pH}pHstart text, p, H, end text of a solution, we can also find [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket:

[\text H^+]=10^{-\text{pH}}\quad\quad\quad\quad\quad\;\;\;\text{(Eq. 1b)}[H+]=10−pH(Eq. 1b)open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket, equals, 10, start superscript, minus, start text, p, H, end text, end superscript, start text, left parenthesis, E, q, point, space, 1, b, right parenthesis, end text

[How do you do logarithm calculations?]

Relating [\text {OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket and \text{pOH}pOHstart text, p, O, H, end text
The \text{pOH}pOHstart text, p, O, H, end text for an aqueous solution is defined in the same way for [\text{OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket:

\text{pOH}=-\log[\text{OH}^-]~\quad\quad\quad\;\;\text{(Eq. 2a)}pOH=−log[OH−] (Eq. 2a)start text, p, O, H, end text, equals, minus, log, open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket, space, start text, left parenthesis, E, q, point, space, 2, a, right parenthesis, end text

For example, if we have a solution with [\text{OH}^-]=1 \times 10^{-12}\text{ M}[OH−]=1×10−12 Mopen bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket, equals, 1, times, 10, start superscript, minus, 12, end superscript, start text, space, M, end text, then we can calculate \text{pOH}pOHstart text, p, O, H, end text using **Eq. 2a**:

\text{pOH}=-\log(1 \times 10^{-12})=12.0pOH=−log(1×10−12)=12.0start text, p, O, H, end text, equals, minus, log, left parenthesis, 1, times, 10, start superscript, minus, 12, end superscript, right parenthesis, equals, 12, point, 0

Given the \text{pOH}pOHstart text, p, O, H, end text of a solution, we can also find [\text{OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket:

10^{-\text{pOH}}=[\text {OH}^-]\quad\quad\quad\quad\quad\;\;\;\text{(Eq. 2b)}10−pOH=[OH−](Eq. 2b)10, start superscript, minus, start text, p, O, H, end text, end superscript, equals, open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket, start text, left parenthesis, E, q, point, space, 2, b, right parenthesis, end text

Relating \text{pH}pHstart text, p, H, end text and \text{pOH}pOHstart text, p, O, H, end text
Based on equilibrium concentrations of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript and \text{OH}^-OH−start text, O, H, end text, start superscript, minus, end superscript in water, the following relationship is true for any aqueous solution at 25\,^\circ\text{C}25∘C25, degrees, start text, C, end text:

\text{pH}+\text{pOH}=14~~\quad\quad\quad\quad\quad\quad\quad\quad\text{(Eq. 3)}pH+pOH=14 (Eq. 3)start text, p, H, end text, plus, start text, p, O, H, end text, equals, 14, space, space, start text, left parenthesis, E, q, point, space, 3, right parenthesis, end text

This relationship can be used to convert between \text{pH}pHstart text, p, H, end text and \text{pOH}pOHstart text, p, O, H, end text. In combination with **Eq. 1a/b** and **Eq. 2a/b**, we can always relate \text{pOH}pOHstart text, p, O, H, end text and/or \text{pH}pHstart text, p, H, end text to [\text{OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket and [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket. For a derivation of this equation, check out the article on the autoionization of water.

Example 1: Calculating the \text{pH}pHstart text, p, H, end text of a strong base solution
If we use 1.0\text{ mmol}1.0 mmol1, point, 0, start text, space, m, m, o, l, end text of \text{NaOH}NaOHstart text, N, a, O, H, end text to make 1.0\text{ L}1.0 L1, point, 0, start text, space, L, end text of an aqueous solution at 25\,^\circ\text{C}25∘C25, degrees, start text, C, end text, what is the \text{pH}pHstart text, p, H, end text of this solution?

We can find the \text{pH}pHstart text, p, H, end text of our \text{NaOH}NaOHstart text, N, a, O, H, end text solution by using the relationship between [\text{OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket, \text{pH}pHstart text, p, H, end text, and \text{pOH}pOHstart text, p, O, H, end text. Let's go through the calculation step-by-step.

Step 1. Calculate the molar concentration of \text{NaOH}NaOHstart text, N, a, O, H, end text
Molar concentration is equal to moles of solute per liter of solution:

\text{Molar concentration}=\dfrac{\text{mol solute}}{\text{L solution}}Molar concentration=L solutionmol solutestart text, M, o, l, a, r, space, c, o, n, c, e, n, t, r, a, t, i, o, n, end text, equals, start fraction, start text, m, o, l, space, s, o, l, u, t, e, end text, divided by, start text, L, space, s, o, l, u, t, i, o, n, end text, end fraction

To calculate the molar concentration of \text{NaOH}NaOHstart text, N, a, O, H, end text, we can use the known values for the moles of \text{NaOH}NaOHstart text, N, a, O, H, end text and the volume of solution:

\begin{aligned}\text{[NaOH]}&=\dfrac{1.0\text{ mmol NaOH}}{1.0\text{ L}}\\ \\ &=\dfrac{1.0\times10^{-3}\text{ mol NaOH}}{1.0\text{ L}}\\ \\ &=1.0\times10^{-3}\text{ M NaOH}\end{aligned}[NaOH]=1.0 L1.0 mmol NaOH=1.0 L1.0×10−3 mol NaOH =1.0×10−3 M NaOH

The concentration of \text{NaOH}NaOHstart text, N, a, O, H, end text in the solution is 1.0\times10^{-3}\text{ M}1.0×10−3 M1, point, 0, times, 10, start superscript, minus, 3, end superscript, start text, space, M, end text.

Step 2: Calculate [\text{OH}^-]$[OH^-]$open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket based on the dissociation of \text{NaOH}NaOHstart text, N, a, O, H, end text
Because \text{NaOH}NaOHstart text, N, a, O, H, end text is a strong base, it dissociates completely into its constituent ions in aqueous solution:

\text{NaOH}(aq)\rightarrow\text{Na}^+(aq)+\text{OH}^-(aq)$NaOH(aq)\rightarrow Na^+(aq)+OH^-(aq)$start text, N, a, O, H, end text, left parenthesis, a, q, right parenthesis, right arrow, start text, N, a, end text, start superscript, plus, end superscript, left parenthesis, a, q, right parenthesis, plus, start text, O, H, end text, start superscript, minus, end superscript, left parenthesis, a, q, right parenthesis

This balanced equation tells us that every mole of \text{NaOH}NaOHstart text, N, a, O, H, end text produces one mole of \text{OH}^-OH^-start text, O, H, end text, start superscript, minus, end superscript in aqueous solution. Therefore, we have the following relationship between [\text{NaOH}][NaOH]open bracket, start text, N, a, O, H, end text, close bracket and [\text{OH}^-]$[OH^-]$open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket:

[\text{NaOH}]=[\text{OH}^-]=1.0\times10^{-3}\text{ M}$[NaOH]=[OH^-]=1.0\times10^{-3}$ Mopen bracket, start text, N, a, O, H, end text, close bracket, equals, open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket, equals, 1, point, 0, times, 10, start superscript, minus, 3, end superscript, start text, space, M, end text

Step 3: Calculate \text{pOH}pOHstart text, p, O, H, end text from [\text{OH}^-]$[OH^-]$open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket using Eq. 2a
Now that we know the concentration of \text{OH}^-OH^-start text, O, H, end text, start superscript, minus, end superscript, we can calculate \text{pOH}pOHstart text, p, O, H, end text using **Eq. 2a**:

\begin{aligned}\text{pOH}&=-\log[\text{OH}^-]\\ \\ &=-\log(1.0\times10^{-3})\\ \\ &=3.00\end{aligned}$pOH=-\log[OH^-]=-\log(1.0\times10^{-3})=3.00$

The \text{pOH}pOHstart text, p, O, H, end text of our solution is 3.003.003, point, 00.

Step 4: Calculate \text{pH}pHstart text, p, H, end text from \text{pOH}pOHstart text, p, O, H, end text using Eq. 3
We can calculate \text{pH}pHstart text, p, H, end text from \text{pOH}pOHstart text, p, O, H, end text using **Eq. 3**. Rearranging to solve for our unknown, \text{pH}pHstart text, p, H, end text:

\text{pH}=14-\text{pOH}$pH=14-pOH$start text, p, H, end text, equals, 14, minus, start text, p, O, H, end text

We can substitute the value of \text{pOH}pOHstart text, p, O, H, end text we found in **Step 3** to find the \text{pH}pHstart text, p, H, end text:

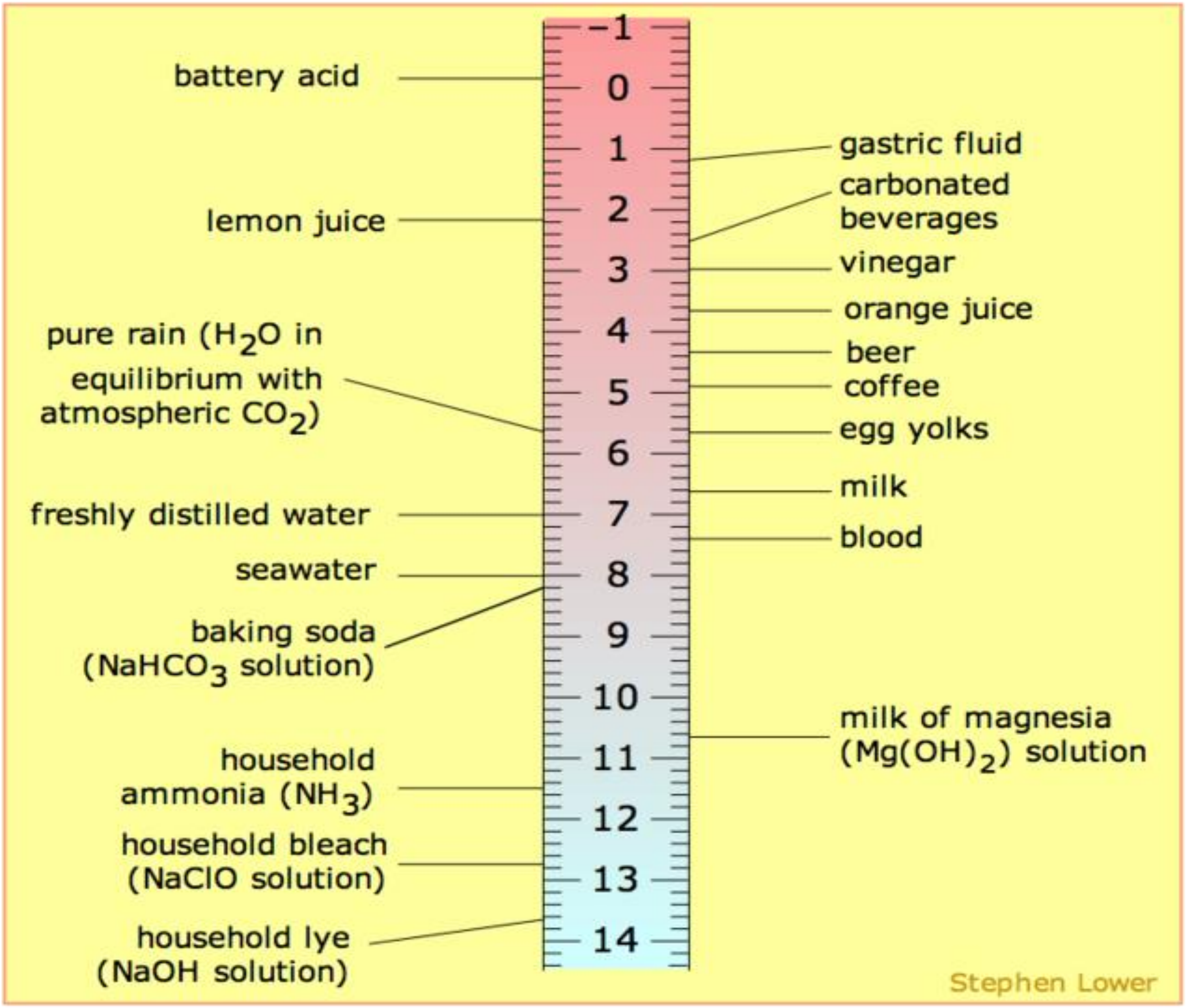
\text{pH}=14-3.00=11.00$pH=14-3.00=11.00$start text, p, H, end text, equals, 14, minus, 3, point, 00, equals, 11, point, 00

Therefore, the \text{pH}pHstart text, p, H, end text of our \text{NaOH}NaOHstart text, N, a, O, H, end text solution is 11.0011.0011, point, 00.

The \text{pH}pHstart text, p, H, end text scale: Acidic, basic, and neutral solutions
Converting [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket to \text{pH}pHstart text, p, H, end text is a convenient way to gauge the relative acidity or basicity of a solution. The \text{pH}pHstart text, p, H, end text scale allows us to easily rank different substances by their \text{pH}pHstart text, p, H, end text value.

The \text{pH}pHstart text, p, H, end text scale is a negative logarithmic scale. The logarithmic part means that \text{pH}pHstart text, p, H, end text changes by 111 unit for every factor of 101010 change in concentration of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript. The negative sign in front of the log tells us that there is an *inverse relationship* between \text{pH}pHstart text, p, H, end text and [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket: when \text{pH}pHstart text, p, H, end text increases, [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket decreases, and vice versa.

The following image shows a \text{pH}pHstart text, p, H, end text scale labeled with \text{pH}pHstart text, p, H, end text values for some common household substances. These \text{pH}pHstart text, p, H, end text values are for solutions at 25\,^\circ\text{C}25∘C25, degrees, start text, C, end text. Note that it is possible to have a negative \text{pH}pHstart text, p, H, end text value.



The pH scale from -1 to 14.

The pH scale. Acidic solutions have pH values less than 7, and basic solutions have pH values greater than 7. Image from UCDavis ChemWiki, CC BY-NC-SA 3.0 US.

Some important terminology to remember for aqueous solutions at 25\,^\circ\text{C}25∘C25, degrees, start text, C, end text:

- For a *neutral* solution, \text{pH}=7pH=7start text, p, H, end text, equals, 7.
- *Acidic* solutions have \text{pH}<7pH<7start text, p, H, end text, is less than, 7.
- *Basic* solutions have \text{pH}>7pH>7start text, p, H, end text, is greater than, 7.

The lower the \text{pH}pHstart text, p, H, end text value, the more acidic the solution and the higher the concentration of \text H^+H+start text, H, end text, start superscript, plus, end superscript. The higher the \text{pH}pHstart text, p, H, end text value, the more basic the solution and the lower the concentration of \text H^+H+start text, H, end text, start superscript, plus, end superscript. While we could also describe the acidity or basicity of a solution in terms of \text{pOH}pOHstart text, p, O, H, end text, it is a little more common to use \text{pH}pHstart text, p, H, end text. Luckily, we can easily convert between \text{pH}pHstart text, p, H, end text and \text{pOH}pOHstart text, p, O, H, end text values.

Concept check: Based on the \text{pH}pHstart text, p, H, end text scale given above, which solution is more acidic-−minusorange juice, or vinegar?

[Show the answer]

Example 222: Determining the \text{pH}pHstart text, p, H, end text of a diluted strong acid solution
We have 100\text{ mL}100 mL100, start text, space, m, L, end text of a nitric acid solution with a \text{pH}pHstart text, p, H, end text of 4.04.04, point, 0. We dilute the solution by adding water to get a total volume of 1.0\text{ L}1.0 L1, point, 0, start text, space, L, end text.

What is the \text{pH}pHstart text, p, H, end text of the diluted solution?

There are multiple ways to solve this problem. We will go over two different methods.

Method 1. Use properties of the log scale

Recall that \text{pH}pHstart text, p, H, end text scale is a negative logarithmic scale. Therefore, if the concentration of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript decreases by a single factor of 101010, then the \text{pH}pHstart text, p, H, end text will *increase* by 111 unit.

Since the original volume, 100\text{ mL}100 mL100, start text, space, m, L, end text, is one tenth the total volume after dilution, the concentration of \text H^+H+start text, H, end text, start superscript, plus, end superscript in solution has been reduced by a factor of 101010. Therefore, the \text{pH}pHstart text, p, H, end text of the solution will increase 111 unit:

\begin{aligned}\text{pH}&=\text{original pH}+1.0 \\ \\ &=4.0+1.0\\ \\ &=5.0\end{aligned}pH =original pH+1.0=4.0+1.0=5.0

Therefore, the \text{pH}pHstart text, p, H, end text of the diluted solution is 5.05.05, point, 0.

Method 2. Use moles of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript to calculate \text{pH}pHstart text, p, H, end text
Step 1: Calculate moles of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript
We can use the \text{pH}pHstart text, p, H, end text and volume of the original solution to calculate the moles of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript in the solution.

\begin{aligned}\text{moles H}^+&=[\text H^+]_{initial} \times \text{volume}\\ \\ &=10^{-\text{pH}}\,\text M \times \text {volume}\\ \\ &=10^{-4.0}\,\text M \times {0.100\text{ L}}\\ \\

&=1.0 \times 10^{-5}\,\text {mol H}^+\end{aligned}moles H+=[H+]*initial* ×volume=10−pHM×volume=10−4.0M×0.100 L=1.0×10−5mol H+

Step 2: Calculate molarity of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript after dilution
The molarity of the diluted solution can be calculated by using the moles of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript from the original solution and the total volume after dilution.

\begin{aligned}[\text{H}^+]_{final}&=\dfrac{\text{mol H}^+}{\text{L solution}}\\ \\ &=\dfrac{1.0 \times 10^{-5}\,\text {mol H}^+}{1.0\,\text{L}}\\ \\ &=1.0 \times 10^{-5}\,\text M\end{aligned}[H+]*final*=L solutionmol H+=1.0L1.0×10−5mol H+=1.0×10−5M

Step 3: Calculate \text{pH}pHstart text, p, H, end text from [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket
Finally, we can use **Eq. 1a** to calculate \text{pH}pHstart text, p, H, end text:

\begin{aligned}\text{pH}&=-\log[\text{H}^+]\\ \\ &=-\text{log}(1.0 \times 10^{-5})\\ \\ &=5.0\end{aligned}pH=−log[H+]=−log(1.0×10−5)=5.0

Method 2 gives us the same answer as **Method 1**, hooray!

In general, **Method 2** takes a few extra steps, but it can always be used to find changes in \text{pH}pHstart text, p, H, end text. **Method 1** is a handy shortcut when changes in concentration occur as multiples of 101010. **Method 1** can also be used as a quick way to estimate \text{pH}pHstart text, p, H, end text changes.

Relationship between \text{pH}pHstart text, p, H, end text and acid strength
Based on the equation for \text{pH}pHstart text, p, H, end text, we know that \text{pH}pHstart text, p, H, end text is related to [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket. However, it is important to remember that \text{pH}pHstart text, p, H, end text is *not* always directly related to acid strength.

The strength of an acid depends on the amount that the acid dissociates in solution: the stronger the acid, the higher [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket at a given acid concentration. For example, a 1.0\,\text M1.0M1, point, 0, start text, M, end text solution of strong acid \text{HCl}HClstart text, H, C, l, end text will have a higher concentration of \text{H}^+H+start text, H, end text, start superscript, plus, end superscript than a 1.0\,\text M1.0M1, point, 0, start text, M, end text solution of weak acid \text{HF}HFstart text, H, F, end text. Thus, for two solutions of monoprotic acid at the same concentration, \text{pH}pHstart text, p, H, end text will be proportional to acid strength.

More generally though, both acid strength and concentration determine [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket. Therefore, we can't always assume that the \text{pH}pHstart text, p, H, end text of a strong acid solution will be lower than the \text{pH}pHstart text, p, H, end text of a weak acid solution. The acid concentration matters too!

Summary

Hand holding wet pH paper with four stripes (from left to right): orange, green-brown, yellow, and red-orange. The paper is held up for comparison against a reference chart of pH values and colors. The wet paper matches the pH 7 on the reference.

Indicator paper can be used to measure the pH of aqueous solutions. The color of the indicator paper in this picture matches a pH value of 7. [Photo](#) from Wikimedia Commons, [CC BY-SA 2.5](#)

- We can convert between [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket and \text{pH}pHstart text, p, H, end text using the following equations:

\begin{aligned}\text{pH}&=-\log[\text{H}^+]\\ \\ [\text H^+]&=10^{-\text{pH}}\end{aligned}pH[H+]=−log[H+]=10−pH

- We can convert between [\text{OH}^-][OH−]open bracket, start text, O, H, end text, start superscript, minus, end superscript, close bracket and \text{pOH}pOHstart text, p, O, H, end text using the following equations:

\begin{aligned}\text{pOH}&=-\log[\text{OH}^-]\\ \\ [\text {OH}^-]&=10^{-\text{pOH}}\end{aligned}pOH[OH−]=−log[OH−]=10−pOH

- For every factor of 101010 *increase* in concentration of [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket, \text{pH}pHstart text, p, H, end text will *decrease* by 111 unit, and vice versa.

- For any aqueous solution at 25\,^\circ\text{C}25∘C25, degrees, start text, C, end text:

\text{pH}+\text{pOH}=14pH+pOH=14start text, p, H, end text, plus, start text, p, O, H, end text, equals, 14.

- Both acid strength and concentration determine [\text{H}^+][H+]open bracket, start text, H, end text, start superscript, plus, end superscript, close bracket and \text{pH}pHstart text, p, H, end text.

[Attributions and references]

Problem 1: Calculating the pH of a strong base solution at 25\,^\circ\text{C}25∘ C25, degrees, start text, C, end text

We make 200\text{ mL}200 mL200, start text, space, m, L, end text of a solution with a 0.025\text{ M}0.025 M0, point, 025, start text, space, M, end text concentration of \text{Ca(OH)}_2Ca(OH)2start text, C, a, left parenthesis, O, H, right parenthesis, end text, start subscript, 2, end subscript. The solution is then diluted to 1.00\text{ L}1.00 L1, point, 00, start text, space, L, end text by adding additional water.