# A weak acid

## Introduction

This problem contains little information. Students will have to recall information learned earlier in their course about solution chemistry, pH and weak acids or find the information in textbooks, and then apply this knowledge to the problem in a creative way.

Teachers who have not used the problems before should read the section using the problems before starting.

## Prior knowledge

Solution chemistry ie weak acids and strong acids, Ka (or pKa) and pH. A detailed knowledge is unnecessary as students are encouraged to consult textbooks and data books during the exercise.

## Equipment

Scientific calculators, data books to look up strengths of weak acids and physical chemistry textbooks should be available for reference.

## Group size

3–4.

## Possible solutions

Students should refer to data books and select a suitable acid. Possibilities include:

| Acid | $K_a$ | $pK_a$[1] |
|---|---|---|
| Aminoethanoic | $1.4 \times 10^{-10}$ | 9.87 |
| Boric2 | $7.2 \times 10^{-10}$ | 9.14 |
| Ethanoic | $1.4 \times 10^{-5}$ | 4.76 |
| Hydrocyanic | $4.9 \times 10^{-10}$ | 9.31 |
| Nitrous | $5.4 \times 10^{-4}$ | 3.27 |
| Phenol | $1.0 \times 10^{-10}$ | 10.00 |

This example concerns an aqueous solution of HCN[3]

$$\mathrm{HCN(aq)} \Leftrightarrow \mathrm{H^+(aq)} + \mathrm{CN^-(aq)}$$

$$K_a = \frac{[\mathrm{H^+(aq)}][\mathrm{CN^-(aq)}]}{[\mathrm{HCN(aq)}]} = \frac{[\mathrm{H^+(aq)}]^2}{[\mathrm{HCN(aq)}]}$$

$$= 4.9 \times 10^{-10}$$

Students will have to decide on the concentration of the acid solution, 0.10 mol dm$^{-3}$ will be used in the following calculations:

$[H^+(aq)]^2 = 4.9 \times 10^{-10} \times 0.10$ (assuming little HCN dissociates)
$[H^+(aq)] = 7.0 \times 10^{-6}$ mol dm$^{-3}$ (pH = 5.2)

(This ignores the contribution of the ionisation of water to the concentration of $H^+(aq)$ – a reasonable assumption even for phenol)

To show what this means, students could:

a) compare this figure with say water and a strong acid, or
b) manipulate the figures for the acid itself.

## a. comparing the weak acid with water and a strong acid

In water, $[H^+(aq)] = 1.0 \times 10^{-7}$ mol dm$^{-3}$
0.1 mol dm$^{-3}$ HCN, $[H^+(aq)] = 7.0 \times 10^{-6}$ mol dm$^{-3}$
0.1 mol dm$^{-3}$ HCl, $[H^+(aq)] = 1.0 \times 10^{-1}$ mol dm$^{-3}$

The ratio of [H+(aq)] in the three liquids is
$1.0 \times 10^{-7} : 7.0 \times 10^{-6} : 1.0 \times 10^{-1}$
or 1 : 70 : 1 000 000

This shows that the weak acid is closer to water than to a strong acid in terms of $H^+(aq)$ ion concentration. For every $H^+(aq)$ in the HCN, there are about 14 000 $H^+(aq)$ in the HCl. Students who use this approach should attempt to put the numbers into context, eg:

- 14 000 is the approximate number of students at a university such as Glasgow; and
- the contents of 14 000 one litre bottles of lemonade would occupy a cube with side 2.5 m.

## b. manipulating the figures for the weak acid

The cyanide ion concentration is the same as $[H^+(aq)]$ ie $7.0 \times 10^{-6}$ mol dm$^{-3}$, and the concentration of unionised HCN is $0.10 - 7.0 \times 10^{-6}$ mol dm$^{-3}$, effectively 0.10 mol dm$^{-3}$. Students have been asked to consider the number of ions and molecules in a solution, so they will use Avogadro's number; they could also calculate the figures for a smaller volume, eg or 1 cm$^3$ or 1 drop.

| **Species** | **$H^+(aq)$** | **CN(aq)** | **HCN(aq)** | **Water** |
|---|---|---|---|---|
| Moles of individual species in 1 dm$^3$ | $7.0 \times 10^{-6}$ | $7.0 \times 10^{-6}$ | 0.10 | 55 |
| Number of individual species in 1 dm$^3$ | $4.2 \times 10^{18}$ | $4.2 \times 10^{18}$ | $6.0 \times 10^{22}$ | $3.3 \times 10^{25}$ |
| Number of individual species in 1 drop (*ca* 0.05 cm$^3$) | $2.1 \times 10^{14}$ | $2.1 \times 10^{14}$ | $3.0 \times 10^{18}$ | $1.65 \times 10^{21}$ |

Compare these figures with:

- the UN estimate for the 1990 world population of 5.25 x 109;
- the Earth–Sun distance of 1.5 x 1011 m; and

- the distance to the nearest star (Proxima Centauri) is 1.5 x 1017 m.

See note 5 for calculation of α, the degree of dissociation of the acid.
To get meaningful numbers, students could calculate ratios from the table, such as:

- for every $H^+$(aq) ion there are 3.3 x 1025/4.2 x 1018 (about 8 million) molecules of water;
- for every $H^+$(aq) ion there are 6 x 1022/4.2 x 1018 (about 14 000) molecules of HCN; and
- for every HCN molecule there are 3.3 x 1025/6.0 x 1022 (about 555) molecules of water.

These ratios are more meaningful than the raw numbers and could form the basis of a group's presentation. The first figure (8 million) is comparable with the population of:

- Greater London (6.4 million);
- Scotland (5 million); and
- Eire (3.5 million).

## Suggested approach

During trialling the following instructions were given to students and proved to be extremely effective:

1. Working as a group, discuss the problem and how you are going to solve it. You can divide the work amongst you but if you do so, keep one another informed of progress.
   Such discussion can play a vital part in working out possible solutions to open-ended problems like this. Several minds working on a problem together can stimulate ideas that one on its own could not manage.
2. Write a brief account of your ideas.
3. Working as a group, prepare a short (ca 5 minute maximum) presentation, aimed at 14- to 16-year-old school students but to be delivered to the rest of your class. As far as possible each group member should take part; any method of presentation can be used such as a blackboard or overhead projector.
   Outline the problem and then present your solution. After the presentation, be prepared to answer questions and to discuss what you did with the rest of the class.

## Notes

1. The trials showed that many students were uncomfortable dealing with logarithms and preferred using $K_a$ rather than $pK_a$.
2. This is not a monoprotic weak acid, but can be treated as one as the three dissociation constants are so different $pK_{a1}$ 9.14, $pK_{a2}$ 12.74 and $pK^{a3}$ 13.80.
3. There was a tendency for students to apply the formulae connecting pH, $pK_a$ and concentration blindly, and indeed incorrectly, and it is recommended that an approach going back to first principles as set out here is preferable.
4. For a 0.10 mol $dm^{-3}$ solution of phenol, the [$H^+$(aq)] calculated as above is 3 x $10^{-6}$ mol $dm^{-3}$; adding [$H^+$(aq)] of $10^{-7}$ mol $dm^{-3}$ from water gives a total [$H^+$(aq)] of 3.25 x $10^{-6}$ mol $dm^{-3}$.
5. Although α doesn't help toward the objective of trying to set these numbers into context

α = [$H^+$(aq)] /c where c = the concentration of the acid (0.10 mol $dm^{-3}$) = 7.0 x $10^{-6}$ /0.10 = 7.0 x $10^{-5}$ or 7.0 x $10^{-3}$ %.

I. What does ‘weak’ mean in terms of the number of ions and molecules in a solution of a weak acid? Look up any monoprotic (monobasic) weak acid in a data book. Starting from its Ka (or $pK_a$) value, calculate or find as much information as you need to show what is meant by ‘weak’ in weak acid.

II. How would you explain the meaning of ‘weak’ in the term weak acid to students aged 14 to 16 who are studying chemistry?

You should refer to any sources of information that you think might help such as your notebooks, textbooks and data books. Ask for assistance if you get stuck.