Republic of Rwanda
Ministry of Education

RTB | RWANDA TVET BOARD

# RQF LEVEL 5

## GENAC502
## ALL CONCERNED TRADE

## Applied Chemistry

## TRAINEE'S MANUAL

APRIL 2025

Republic of Rwanda
Ministry of Education

RTB | RWANDA TVET BOARD

# APPLY BASICS OF ANALYTICAL CHEMISTRY

2025

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# LIST OF ABBREVIATIONS AND ACRONYMS

**CBET:** Competence Base Education and Training

**RQF:** Rwanda Qualification Framework

**RTB:** Rwanda TVET Board

**TVET:** Technical and Vocational Education and Training

**EU:** European Union

**MS:** Mass spectrometry

**EMF:** Electromagnetic Field

**e.m.f:** Electromotive force

# INTRODUCTION

This trainee's manual encompasses all necessary skills, knowledge and attitudes required to **Applied Chemistry** Students undertaking this module shall be exposed to practical activities that will develop and nurture their competences. The writing process of this training manual embraced competency-based education and training (CBET) philosophy by providing practical opportunities reflecting real life situations.

The trainee's manual is subdivided into units, each unit has got various topics. You will start with a self-assessment exercise to help you rate yourself on the level of skills, knowledge and attitudes about the unit.

A discovery activity is followed to help you discover what you already know about the unit.

After these activities, you will learn more about the topics by doing different activities by reading the required knowledge, techniques, steps, procedures and other requirements under the key facts section, you may also get assistance from the trainer. The activities in this training manual are prepared such that they give opportunities to students to work individually and in groups.

After going through all activities, you shall undertake progressive assessments known as formative and finally conclude with your self-reflection to identify your strengths, weaknesses and areas for improvement.

Do not forget to read the point to remember the section which provides the overall key points and takeaways of the unit.

# UNIT 1: DIFFERENTIATE QUALITATIVE AND QUANTITATIVE CHEMICAL ANALYSIS

## Unit summary

This unit provides you with the knowledge, skills and attitudes required to analyze a sample qualitatively and quantitatively by considering the appropriate factors and using suitable method.

## Self-Assessment: Unit 1

1. Referring to the unit illustrations above discuss the following:
   a. What do the illustrations show?
   b. What is the difference between the different images in the illustration?
   c. What do you think this unit is about based on the illustration?
2. Fill in and complete the self-assessment table below to assess your level of knowledge, skills and attitudes under this unit.
   a. There is no right or wrong way to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.
   b. Think about yourself: do you think you have the knowledge, skills or attitudes to do the task? How well?
   c. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills and attitudes.
3. At the end of this unit, you will assess yourself again.

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Relate qualitative and quantitative analysis to know the composition of any sample | | | | | |
| Explain the change in factors that would help to know the quality of a sample | | | | | |
| Differentiate qualitative and | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| quantitative analysis | | | | | |
| Distinguish inorganic and organic qualitative analysis | | | | | |
| Identify the methods for qualitative and quantitative analysis | | | | | |
| Explain the principle behind each qualitative method | | | | | |
| Demonstrate the ability to analyze and interpret the chemical composition of samples | | | | | |
| Recognize the quantitative methods of analysis | | | | | |
| Explain the basic principles of stoichiometry | | | | | |

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Identify the change in factors that would help to know the amount of substance | | | | | |
| Selects appropriate analytical methods based on sample properties, desired sensitivity, and selectivity | | | | | |
| Integrate qualitative and quantitative data to provide a comprehensive understanding of a sample | | | | | |
| Clearly present qualitative and quantitative findings | | | | | |
| Evaluate the effectiveness of different qualitative and quantitative methods | | | | | |
| Explain the application of chemical analysis | | | | | |

## Key Competencies:

| Knowledge | Skills | Attitudes |
|---|---|---|
| 1. Define analytical chemistry | 1. Demonstrate proficiency in various analytical techniques | 1. Uphold high ethical standards in all aspects of analytical work |
| 2. Differentiate between qualitative and quantitative analysis | 2. Interpret observable phenomena to identify the presence of specific compounds | 2. Demonstrate meticulous attention to detail in both qualitative and quantitative analyses |
| 3. Distinguish between inorganic and organic qualitative analysis | 3. Interpret observable reactions to deduce the presence of specific ions. | 3. Have an open-mind to consider all possibilities and re-evaluate methods and hypotheses when necessary. |
| 4. Describe various qualitative methods | 4. Identify and differentiate between flame colors produced by various metal ions accurately | 4. A willingness to adapt to different metals and their behavior in the flame |
| 5. Explain the principle behind each qualitative method | 5. Extract the tea from tea bag using to understand the principle behind extraction | 5. Have patience while applying qualitative methods |

| Knowledge | Skills | Attitudes |
|---|---|---|
| 6. Recognize and explain the factors influencing qualitative analysis | 6. Analyze and interpret the chemical composition of samples | 6. Apply critical thinking when evaluating the factors influencing qualitative analysis and their potential impact on results. |
| 7. Define quantitative analysis | 7. Interpret quantitative data effectively | 7. Have the ability to persist through challenges or unexpected results in data interpretation |
| 8. Describe various quantitative methods | 8. Perform calculations correctly is crucial, especially when determining concentrations in titrations | 8. Strive for high levels of accuracy and precision in calculations. |
| 9. Explain the factors that influence quantitative analysis | 9. Selects appropriate analytical methods based on sample properties, desired sensitivity, and selectivity | 9. A willingness to consider alternative explanations and to learn from mistakes. |
| 10. Discuss the application of qualitative and quantitative analysis | 10. Integrate qualitative and quantitative data to provide a comprehensive understanding of a sample | 10. Be prepared to conduct multiple tests to confirm findings, especially in complex mixtures. |

## Discovery activity:

### Task 1:

1. Referring to your experience in qualitative and quantitative chemical analysis answer the following questions:
    a. Define analytical chemistry
    b. Describe the difference between the qualitative and quantitative chemical analysis
    c. What are some of the key factors that differentiate organic qualitative analysis from inorganic qualitative analysis?
    d. Why is it important to determine the mass or volume of constituents in a chemical sample
    e. How do color, odor, melting point, and boiling point help in identifying chemical substances?
    f. How can volumetric methods, such as titration, be used to determine the concentration of an unknown acid or base in solution?
    g. What factors must be considered when conducting a quantitative analysis
    h. How can quantitative analysis be applied in real-world scenarios, such as in pharmaceuticals or environmental monitoring
    i. Why is it important to determine the mass or volume of constituents in a chemical sample?

## Topic 1.1: Qualitative chemical analysis

### Activity 1: Problem Solving

**Task 2:**

Tea is one of the most popular beverages worldwide, made from the leaves of the Camellia sinensis plant. Different varieties of tea (green tea, black tea, herbal tea, etc.) vary in their chemical composition, influencing their flavor, color, and health benefits.

Referring to the scenario above, do the following

a) Identify the qualitative method used to make tea from tea leaves.

b) Discuss qualitative methods that could be employed to analyze the volatile compounds in tea that contribute to its aroma

c) Describe the methods of qualitative analysis that can be used to determine the chemical composition of a substance.

d) Describe the qualitative method that you could use to test the presence of heavy metals (such as lead or arsenic).

e) If you were to conduct a qualitative analysis of a substance, what factors would you consider to ensure that your sample represents accurately the whole batch?

## Key Facts 1.1: Qualitative chemical analysis

- **Introduction to analytical chemistry**

| Analytical chemistry | Sample |
|---|---|
| **Analytical chemistry:** is the branch of chemistry that focuses on the techniques and methods used to identify and quantify the chemical composition of substances. | **Sample:** is a portion or subset of material selected from a larger quantity of substance, which is used for analysis to represent the whole. |

| Qualitative chemical analysis | Quantitative chemical analysis |
|---|---|
| **Qualitative chemical analysis** is a branch of analytical chemistry that focuses on identifying the chemical components present in a sample | **Quantitative chemical analysis** is a branch of analytical chemistry that focuses on determining the amount or concentration of a specific substance in a sample. |

✓ **Types of qualitative chemical analysis**

| Organic qualitative analysis | inorganic qualitative analysis |
|---|---|

| | |
|---|---|
| **Organic qualitative analysis** is a branch of analytical chemistry that focuses on identifying the functional groups and types of molecules present in an organic compound | **Inorganic qualitative analysis** is a branch of analytical chemistry that involves identifying the constituents or ions present in an inorganic substance |

- **Sampling** is the process of collecting a representative portion of a material or substance for analysis.
  - The goal is to ensure that the sample accurately reflects the characteristics of the entire population from which it was taken.
  - Proper sampling is crucial because incorrect or biased samples can lead to erroneous results in the analysis.
  - Enough sample must be collected for the required analyses.
  - Larger samples generally reduce the impact of random errors
  - Thoroughly mixing the sample can ensure homogeneity, especially for solids.

- **Types of qualitative methods**

  These methods focus on detecting the presence or absence of specific chemical substances or elements by observing physical or chemical reactions. These include: **Flame test, Distillation, Extraction and precipitation**

  - **Flame test:** is a qualitative analytical technique used to identify the presence of certain metal ions in a sample based on the characteristic colors they emit when heated in a flame.
    - **The principle of the flame test** is based on the phenomenon of atomic emission spectroscopy, where metal ions in a sample are excited by heat from a flame, causing them to emit light at characteristic wavelengths
  - **Distillation** is a separation process used to separate components of a mixture based on differences in their boiling points.
    - **The principle of distillation relies** on the fact that when a mixture is heated, the components with lower boiling points will vaporize first, leaving behind

components with higher boiling points. The vapor can then be condensed back into liquid form, allowing the separation of the different components.

- **The main type of distillation** include: Simple distillation, Fractional distillation, Vacuum distillation, Steam distillation, Azeotropic distillation, Continuous distillation, Batch distillation
  - **Simple distillation** is used to separate liquids with significantly different boiling points.
  - **Fractional distillation** is used to separate a mixture of liquids with boiling points that are close together.
  - **Vacuum distillation** is used to purify compounds that are heat-sensitive or have high boiling points.
  - **Steam distillation** is used to isolate heat-sensitive compounds from a mixture.
  - **Azeotropic distillation** is a specialized technique used to separate two or more liquids that has a constant boiling point and composition.
  - **Continuous distillation** is a process used to separate components of a liquid mixture in a continuous flow system.
  - **Batch distillation** is a type of distillation where the entire amount of the liquid mixture is processed in a single batch.

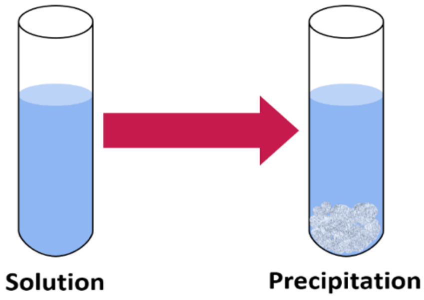
✓ **Extraction:** is a technique used to separate a compound from a mixture by taking advantage of its different solubilities in two immiscible solvents.

- **The principle behind extraction** relies on the differential solubility of different components of a mixture. A solvent selectively dissolves the desired compound, leaving behind impurities or other substances that do not dissolve as easily
- **The main types of extraction** include: liquid-liquid extraction, solid-liquid extraction, acid-base extraction, Supercritical fluid extraction, Microwave-assisted extraction, Ultrasound-Assisted Extraction,
  - **Liquid-Liquid Extraction (Solvent Extraction):** Involves the separation of a compound between two immiscible liquid phases.

- **Solid-Liquid Extraction (Soxhlet Extraction):** Involves extracting a solid material with a solvent.
- **Acid-Base Extraction:** Exploits the acid-base properties of compounds to separate them.
- **Supercritical Fluid Extraction (SFE):** Utilizes a supercritical fluid (e.g., carbon dioxide) as the solvent. Supercritical fluids have properties of both liquids and gases, allowing for efficient extraction of compounds.
- **Microwave-Assisted Extraction (MAE):** Uses microwave radiation to heat the solvent and sample, accelerating the extraction process**.**
- **Ultrasound-Assisted Extraction (UAE):** Employs ultrasonic waves to enhance mass transfer and improve extraction efficiency.

✓ **Precipitation:** is a process in which a solid (the precipitate) forms and separates from a solution as a result of a chemical reaction or a change in conditions.

- **The principle of precipitation** is based on the solubility product constant (Ksp), which is the equilibrium constant for the dissolution of a sparingly soluble ionic compound in water. When the concentration of ions in the solution exceeds the solubility product the ions combine to form a solid compound, which then precipitates out of the solution.



[1]Figure 1 Formation of precipitate

- **The types of precipitation based** on the way the precipitate forms or the conditions that lead to its formation include: Double displacement precipitation, Nucleation precipitation, Co-precipitation, crystallization precipitation, Selective precipitation, instantaneous precipitation, slow precipitation, precipitation by solvent evaporation.

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[1] https://www.expii.com/t/what-are-precipitates-definition-overview-8574

   - **Double displacement precipitation:** This occurs when two ionic compounds in aqueous solution react, and one of the products formed is insoluble, resulting in the formation of a precipitate.
   - **Nucleation precipitation:** involves the initial formation of small particles or "nuclei" that later grow into larger precipitates.
   - **Co-precipitation** occurs when impurities or other substances are trapped within the precipitate.
   - **Crystallization precipitation** is a slow process in which the solute forms large, well-defined crystals over time.
   - **Selective precipitation** involves selectively precipitating a specific ion from a mixture of ions in solution.
   - **Instantaneous precipitation** occurs when two highly concentrated solutions are mixed, resulting in an immediate formation of a precipitate.
   - **Slow precipitation**: the precipitate forms gradually over time, often in the form of larger crystals

- **Factors/criteria considered for qualitative chemical analysis**

  There are numerous factors to consider while conducting qualitative analysis of any chemical but the crucial ones are **Color, Odor, melting and boiling point, solubility, radioactivity and reactivity.**

  - ✓ **The color** comes from the excitation of electrons due to an absorption of energy performed by the chemical therefor different chemical differentiated by their color.
  - ✓ **An odor** primarily originates from a compound volatilizing at ambient temperature and thus reaching the nose. Therefore, both organic and inorganic molecules may have a smell.
  - ✓ **Melting point and boiling point:** Comparing the observed melting point of a sample to known values can help identify the substance.
  - ✓ **Solubility** is used to identify the presence of various substance as they have different solubility.

**Radioactivity/Reactivity:** various chemicals have different reactivity and some are radioactive isotopes.

## Activity 2: Guided Practice

### Task 3:

Mrs. Kamanda, a skilled homemaker, is addressing a household situation where a mixture of salt and sand has accidentally contaminated some cooking ingredients. The mixture has been collected, and Mrs. Kamanda must ensure that the sand is completely removed, leaving only the salt for future use in cooking. Once the separation is complete, she performs a simple qualitative check to confirm that the salt has been successfully isolated and to assess its purity before using it in her family's meals.

Referring to the scenario above, perform the following tasks

1. Take a prepared mixture of a 100g of salt (NaCl) and 30 g of sand
2. Separate the insoluble sand from the saltwater solution.
3. Use distillation to purify the water from the saltwater solution.
4. Analyze the distillate to confirm its purity and composition

## Activity 3: Application

### Task 4:

AGROFET fertilizer manufacturing plant needs to analyze a new batch of NPK fertilizer to verify that it meets the required nutrient content before releasing the product to the market.  As the quality control laboratory officer of that company, you are asked to perform the needed analysis.

Referring to the scenario above, perform the following tasks

1. Collect a sample of NPK fertilizer to be analyzed
2. Homogenize the sample to ensure uniformity
3. Perform a flame test to check the presence of potassium ions characterized by a violet flame

# Topic 1.2: Quantitative chemical analysis

## Activity 1: Problem Solving

### Task 5:

A local community in Musanze District has raised concerns about potential water contamination from a nearby industrial site. As a team of environmental scientists, you are tasked with conducting a quantitative analysis to investigate the water quality in the area

Referring to the scenario above, do the following

1. Discuss the primary goal of using quantitative chemical analysis in water quality testing
2. Identify the primary advantage of performing quantitative analysis in water quality testing
3. Describe chemical methods to analyze a substance quantitatively
4. Identify any 2 factors that scientist should consider while conducting this analysis.
5. Explain how this analysis is related to the application of chemical analysis

## Key Facts 1.2a: Quantitative chemical analysis

- **Quantitative methods**
  - ✓ **Volumetric analysis/titration:** is a quantitative analytical technique used to determine the concentration of a specific substance (analyte) in a solution.

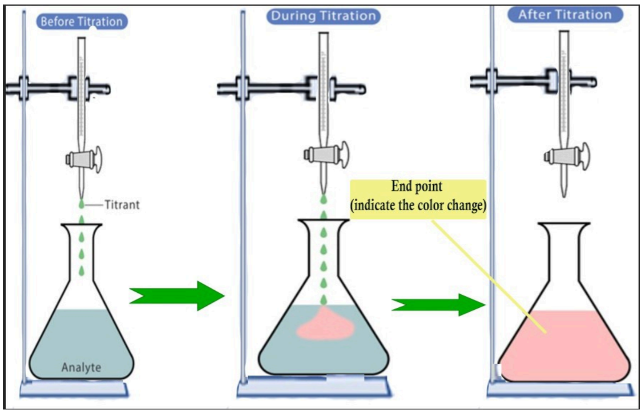


*Figure 2 Titration process*

- The principal of titration is based on A titrant of known concentration is added to the analyte until the reaction reaches the equivalence point.
- The concentration of the analyte can be calculated using the following formula:

  **$C_1V_1 = C_2V_2$** where **$C_1$** is the concentration of titrant **$V_1$** is the volume of titrant **$C_2$** is the concentration of analyte and **$V_2$** is the volume of analyte.
- The main types of titration include: Acid-base titration, Redox titration, precipitation titration and complexometric titration.
  - **Acid-Base Titration**: Determines the concentration of an acid or a base in a solution by neutralizing it with a base or acid, respectively.
  - **Redox Titration:** Based on the transfer of electrons in redox reactions.
  - **Precipitation Titration**: Involves the formation of a precipitate.
  - **Complexometric Titration**: Involves the formation of a complex.

✓ **Gravimetric method:** involves measuring the mass of an analyte or a precipitate formed from a reaction.

- It is based on **the principle** that the amount of a substance can be determined by converting it to a stable, pure form and weighing it.
- Used for determining the concentration of metal ions, sulfates, and other compounds in a sample.
- Types of Gravimetric Analysis includes; Precipitation Gravimetry, Volatilization Gravimetry and Electrogravimetry.
  - **Precipitation Gravimetry:** The analyte is precipitated from solution and weighed
  - **Volatilization Gravimetry:** The analyte is volatilized and the loss in mass is measured
  - **Electrogravimetry:** The analyte is deposited on an electrode by electrolysis and weighed

- **Factors/criteria considered for quantitative chemical analysis**

✓ **Density:** is a fundamental physical property of matter that describes the mass of an object or substance per unit volume

- Density (ρ) = $\frac{Mass\ (m)}{Volume\ (v)}$

- Density tells you how tightly matter is packed within a given volume.
- Density is expressed in $g/dm^3$ or $Kg/dm^3$

✓ **Refractive index:** is a fundamental optical property of a material that describes how light propagates through it.

- It is defined as the ratio of the speed of light in a vacuum to the speed of light in the material.
- The refractive index indicates how much the light will bend, or refract, when passing from one medium to another.
- Refractive index = $\frac{speed\ of\ light\ in\ a\ vacuum}{speed\ of\ light\ in\ the\ material.}$
- Speed of light in a vacuum is approximately $3.00\times10^8$ m/s.

✓ **Absorption of light:** is an important factor in quantitative chemical analysis, particularly in techniques like spectrophotometry, where the measurement of light absorbed by a sample is used to determine the concentration of an analyte

✓ **Polarization of light:** Use the interaction of polarized light with chiral molecules to quantify their concentration.

✓ **Electric field:** influences how molecules interact with electromagnetic radiation

- The electric field's role in these techniques enables the detection, quantification, and analysis of chemical substances by providing detailed information about their properties and behaviors in response to the field

✓ **Magnetic field:** Utilizes the interaction between nuclei and a strong magnetic field to determine the structure and composition of molecules.

## Key Facts 1.2b: Applications of chemical analysis

✓ **Water analysis** is essential for monitoring water quality, ensuring its safety for drinking, industrial use, and environmental health.

- Both qualitative and quantitative chemical analysis play crucial roles in detecting contaminants, determining chemical composition, and assessing the purity of water.
- Qualitative analysis focuses on detecting the presence or absence of specific substances in water.

  - Quantitative analysis is used to measure the exact concentration of specific substances in water.
- ✓ **Soil analysis** is an essential process in agriculture, environmental science, and land management to assess soil health, fertility, and potential contamination.
  - Both qualitative and quantitative chemical analysis play significant roles in identifying soil composition, nutrient levels, contaminants, and other factors that influence plant growth, crop yields, and ecosystem sustainability
  - Qualitative analysis in soil testing helps to detect the presence of specific substances, pollutants, or essential nutrients.
  - Quantitative analysis provides precise data on the concentration of various chemical components in the soil.
- ✓ **Food analysis** involves examining the chemical composition, quality, and safety of food products.
  - Both qualitative and quantitative chemical analysis are employed to determine the presence of nutrients, contaminants, additives, and other components that affect the nutritional value, safety, and quality of food.
  - Qualitative analysis in food testing focuses on detecting the presence of specific substances.
  - Quantitative analysis provides exact measurements of the concentration of specific substances in food.
- ✓ **Pharmaceutical analysis** plays a vital role in the development, production, and regulation of drugs.
  - Both qualitative and quantitative chemical analysis are used to ensure the quality, safety, and efficacy of pharmaceutical products.
  - Qualitative analysis involves identifying the presence or absence of specific components in pharmaceutical substances.
  - Quantitative analysis provides precise measurements of the concentration of active ingredients, impurities, and excipients in pharmaceutical formulations.

- ✓ **Fertilizers and pesticides** are essential components of modern agriculture, and their analysis is crucial for ensuring safety, efficacy, and environmental protection.
  - This involves a combination of qualitative and quantitative chemical analysis techniques to determine their composition, purity, and potential contaminants.
  - Both qualitative and quantitative chemical analysis are used to identify and quantify the active ingredients, impurities, and contaminants.

## Activity 2: Guided Practice

### Task 6:

AMAHORO Dairy received 10L of fresh milk. Kamali, the dairy manager wants to test the acidity (Lactic acid concentration) of that fresh milk. As laboratory technician you are tasked to perform the needed analysis.

Referring to the scenario above, perform the following tasks

1. Prepare a 0.1M NaOH solution in 500 ml
2. Titrate 10 ml of fresh milk using prepared NaOH solution and phenolphthalein indicator
3. Perform three trials, record the volume always and calculate the titration volume
4. Determine the acidity (Lactic Acid concentration) of the given milk after titration.
5. Basing on the acidity, provide the conclusion about the given milk as the concentration of fresh milk is ranging between 0.13 and 0.17.

## Activity 3: Application

### Task 7:

ADRACHEM is a chemical production factory specializes in analyzing the purity of raw materials in Rwanda. In 2024 a quality control chemist working for a laboratory tasked with analyzing a sample of a hydrated salt that has been received from a supplier. To determine the amount of volatile compound (water of crystallization) in the sample by measuring the mass before and after heating the sample to remove the volatile component.

Referring to the scenario above, perform the following tasks

1. Weigh a 50g of a sample containing a hydrated salt
2. Heat the sample in an evaporating dish to remove the volatile component.
3. Allow the sample to cool, then reweigh it.
4. Calculate the mass lost and determine the amount of volatile compound present

## Formative Assessment

1. What is the main focus of qualitative chemical analysis?
   a) To determine the concentration of substances in a sample
   b) To identify the chemical components, present in a sample
   c) To measure the mass of an analyte
   d) To separate components of a mixture based on boiling points
2. Which of the following is an example of a technique used in quantitative chemical analysis?
   a) Flame test
   b) Distillation
   c) Titration
   d) Extraction
3. Which of the following is not a factor considered in qualitative chemical analysis?
   a) Color
   b) Melting point
   c) Concentration
   d) Odor
4. What is the primary focus of qualitative chemical analysis in the context of testing fertilizers and pesticides?
   a) Measuring the exact concentration of active ingredients
   b) Detecting the presence or absence of specific contaminants

c) Assessing the overall chemical composition of the product

d) Evaluating the environmental impact of the chemicals.

5. In pharmaceutical analysis, why is quantitative analysis crucial?
   a) To detect impurities in the product
   b) To ensure the presence of active ingredients at proper concentrations
   c) To determine the chemical composition of the product
   d) To separate the ingredients of the formulation
6. Fill in the blank spaces with the appropriate term among the following: the functional groups, ions, atoms, and molecules.
   a) Organic qualitative analysis determines……………………………..in the sample
   b) Inorganic qualitative analysis frequently determines……………………..in the sample
7. The following are statements about qualitative and quantitative chemical analysis, answer by True if the statement is correct or by False if the statement is incorrect
   a) Quantitative analysis is used to measure the concentration of specific substances in a sample.
   b) The concentration of nitrogen in a fertilizer sample can be determined through titration in a quantitative analysis.
   c) Gravimetric analysis involves measuring the mass of an analyte or precipitate formed during a chemical reaction
   d) The principle of the flame test is based on the phenomenon of atomic emission spectroscopy, where metal ions emit light at characteristic wavelengths when excited by heat.
   e) Distillation is a separation process that separates components of a mixture based on differences in their melting points.
8. What does the principle of titration rely on?
9. Identify the primary technique used to determine the concentration of a substance in a solution
10. How can you use a precipitation reaction to determine the concentration of a metal ion in a solution?
11. Explain clearly how reactivity can be used to distinguish different substances
12. What volume of 0.75M HCl is required to neutralize 100ml of 0.01M Ca (OH)2 solution.

13. In petrochemical industry the operator, determine the following information; the melting and boiling point, functional group, structure and types of bonds. How does this be related to qualitative and quantitative analysis?
14. If a fertilizer sample is tested and found to contain 25% nitrogen, what type of analysis has been performed?
15. Discuss the role of fertilizers and pesticides in modern agriculture and the need for chemical analysis to ensure their safety and effectiveness.

## Points to Remember

- ✓ While conducting chemical analysis you start with qualitative chemical analysis followed by quantitative chemical analysis.
- ✓ Always handle samples carefully to avoid contamination or loss of material.
- ✓ Ensure that all glassware and apparatus are clean and free from any previous chemicals.
- ✓ Follow the laboratory rules and regulations during laboratory experiments.
- ✓ When heating samples do so gradually and avoid overheating.
- ✓ For titrations involving pH-sensitive indicators (e.g., acid-base titrations), ensure that pH changes are carefully monitored to identify the equivalence point correctly.
- ✓ In titrations or other reactions, do not delay the observation of color changes, as some reactions can be time-sensitive.

## Self-Reflection

1. Fill in and complete the self-assessment table below to assess your level of knowledge, skills and attitudes after covering this unit.
2. There are no right or wrong ways to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.

3. Think about yourself:

a. Do you think that you have knowledge, skills or attitudes to do the tasks?

b. How well?

4. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills and attitudes.

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Relate qualitative with quantitative analysis to know the composition of any sample | | | | | |
| Explain the change in factors that would help to know the quality of a sample | | | | | |
| Differentiate qualitative and quantitative analysis | | | | | |
| Distinguish inorganic and organic qualitative analysis | | | | | |
| Identify the methods for qualitative and quantitative analysis | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Explain the principle behind each qualitative method | | | | | |
| Demonstrate the ability to analyze and interpret the chemical composition of samples | | | | | |
| Recognize the quantitative methods of analysis | | | | | |
| Explain the basic principles of stoichiometry | | | | | |
| Identify the change in factors that would help to know the amount of substance | | | | | |
| Selects appropriate analytical methods based on sample properties, desired sensitivity, and selectivity | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Integrate qualitative and quantitative data to provide a comprehensive understanding of a sample | | | | | |
| Clearly present qualitative and quantitative findings | | | | | |
| Evaluate the effectiveness of Different qualitative and quantitative methods | | | | | |
| Explain the application of chemical analysis | | | | | |

5. Fill in the table above and share results with the trainer for further guidance.

| Areas of strength | Areas for improvement | Actions to be taken to improve |
|---|---|---|
| **1.**<br>**2.**<br>**3.** | **1.**<br>**2.**<br>**3.** | **1.**<br>**2.**<br>**3.** |

# UNIT 2: DISCUSS SOLUBILITY

## Unit summary

This unit provides you with the knowledge, skills and attitudes required to understand the solubility of sparingly soluble salts. It covers the solubility rules, factors affecting solubility, types of solutions according to solubility. Moreover, it encompasses the relationship between solubility and solubility products with the calculation of solubility and solubility product.

## Self-Assessment: Unit 2

1. Referring to the unit illustrations above discuss the following:
   a. What do the illustrations show?
   b. What do you think this unit is about based on the illustration?
2. Fill in and complete the self-assessment table below to assess your level of knowledge, skills and attitudes under this unit.
   a. There is no right or wrong way to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.
   b. Think about yourself: do you think you have the knowledge, skills or attitudes to do the task? How well?
   c. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills and attitudes.

3. At the end of this unit, you will assess yourself again.

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Recall and apply the solubility rules when faced with practical chemistry problems or experiments. | | | | | |
| Differentiate the components of solution | | | | | |
| Identify which salts are soluble or insoluble in | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| water based on their ionic composition. | | | | | |
| Explain why certain compounds dissolve and others do not | | | | | |
| Recognize the role of solubility in everyday life. | | | | | |
| Predict how solubility will change with temperature and pressure | | | | | |
| Write dissociation equations and express the Ksp for various ionic compounds | | | | | |
| Convert between units ($g/dm^3$ to $mol/dm^3$) and apply these conversions to solve for Ksp. | | | | | |
| Relate the solubility product constant (Ksp) | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| to the solubility of salts | | | | | |
| Determine the solubility product (Ksp) of salts from their known solubility values | | | | | |
| Determining the Molar solubility of salts from their known Ksp values | | | | | |

## Key Competencies:

| Knowledge | Skills | Attitudes |
|---|---|---|
| 1. Define solubility and molar solubility | 1. Interpret l data related to solubility and draw meaningful conclusions. | 1. Strong desire to explore the underlying principles of solubility |
| 2. Differentiate soluble and insoluble salts | 2. Apply the knowledge of solubility in explaining why some substances are soluble while others are not | 2. Willingness to consider different perspectives and approaches to understanding solubility |

| Knowledge | Skills | Attitudes |
|---|---|---|
| 3. List solubility rules for common ionic compounds, | 3. Apply solubility rules to predict whether specific salts will dissolve in water | 3. Paying close attention to the specific rules and exceptions |
| 4. Explain the behavior of ionic compounds in solution | 4. Apply knowledge of ionic bonding, intermolecular forces, and solution chemistry to solve problems | 4. Have a strong desire to explore the behavior of ions in solution |
| 5. Describe the dissociation equations | 5. Write the dissociation equation | 5. Persevere through complex chemical concepts |
| 6. Distinguish types of solutions | 6. Apply the concepts of solubility and saturation to prepare and analyze solutions. | 6. Endure challenging experiments and problem-solving. |
| 7. Discuss the factors that influence solubility | 7. Observe changes in solubility under different conditions. | 7. Willingness to consider different explanations for observed |
| 8. Describe the relationship between solubility and solubility products | 8. Apply the concept of Ksp to solve problems related to solubility. | 8. Persevere through complex calculations and problem-solving. |
| 9. Describe the Ksp expression. | 9. Solve equations involving Ksp expressions | 9. Paying close attention to expressions. |
| 10. Describe the procedures involved in calculating solubility product (Ksp) and solubility | 10. Apply the steps involved in Ksp calculations to calculate solubility product (Ksp) from solubility and vis versa | 10. Persist through complex calculations and problem |

| Knowledge | Skills | Attitudes |
|---|---|---|
| 11. Discuss the use of solubility | 11. Analyze the role of solubility in various applications. | 11. Strong desire to explore the uses of solubility. |

## Discovery activity:

### Task 8:

Mix NaCl with a small amount of water and mix limestone ($CaCO_3$) with water compared with what happens to the solution of salt and water. Moreover, heat the portion of NaCl and water solution with undissolved NaCl and see the change occur. Then answer the following questions.

Referring to the scenario above, do the following

1. Explain what happened when you mixed NaCl with water.
2. Discuss what happened when you mixed $CaCO_3$ with water.
3. Explain what happened when you heated the NaCl and water solution with undissolved NaCl.
4. Describe how temperature affects the solubility of NaCl in water.
5. Discuss the meaning of solubility.

# Topic 2.1: Solubility of sparingly soluble salts

## Activity 1: Problem Solving

### Task 9:

GAKURU is a waiter at UBUMWE coffee shop which prepares coffee for a large group of customers. In their shop, there are two types of coffee: one prepared with sugar and the other without. As a waiter who studied applied chemistry, he is tasked with determining which coffee will dissolve sugar more quickly one brewed with hot water (70°C) and the other brewed with cold water (5°C).

Referring to the scenario above, do the following

1. Discuss how does the temperature of the water affect the solubility of sugar in coffee?
2. Explain the effect of pressure on the solubility of gases (like $CO_2$) in coffee?
3. Describe how does the polarity of sugar and water contribute to this solubility?
4. If you were to use larger sugar crystals instead of granulated sugar, how would this affect the rate of dissolution in both hot and cold coffee

## Key Facts 2.1 Explanation of solubility

- **Explanation solubility**
  - ✓ **Solubility** is the ability of a substance (solute) to dissolve in another substance (solvent), creating a homogeneous solution. It is the maximum mass of solute that should be dissolved into 100g of solvent at a given temperature.
    - Solubility is typically expressed as the maximum amount of solute that can dissolve in a given amount of solvent at a specific temperature and pressure

$$\text{Solubility} = \frac{\text{Mass of solute}}{\text{Mass of solvent}} \times 100$$

  - ✓ **Molar solubility** refers to the number of moles of a solute that can dissolve in a liter of solvent at a given temperature, resulting in a saturated solution.

- It is typically used for solids dissolving in liquids, especially when the solute is ionic (like salts) or molecular.
- Molar solubility is expressed in units of **moles per liter (mol/L)** or **M**

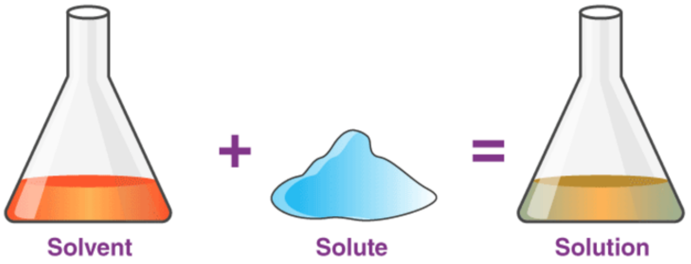
✓ **A solute** is a substance that dissolves in another (solvent) to form a solution

- The amount of solute in a solution is typically less than the amount of solvent.
- Solutes can be solids (e.g., salt), liquids (e.g., alcohol), or gases (e.g., oxygen in water).
- The amount of solute in a given volume of solvent determines the concentration of the solution.

✓ **A solvent** is a substance that dissolves another substance (solute) to form a solution

- In a solution, the solvent typically exists in a larger amount compared to the solute.
- While most solvents are liquids, they can also be gases (e.g., air) or solids (e.g., solid $CO_2$ dissolving in a solid matrix).

✓ **A solution** is a homogeneous mixture of two or more substances, where one substance (the solute) is dissolved in another (the solvent).



[2]

*Figure 3 Components of solution*

✓ **Soluble salt**s are ionic compounds that readily dissolve in water.

- When soluble salts dissolve, they dissociate into their constituent ions, which become surrounded by water molecules.
- Examples of soluble salts include Sodium Chloride (NaCl), Potassium Nitrate ($KNO_3$), Calcium Chloride ($CaCl_2$), Magnesium Sulfate ($MgSO_4$), and Ammonium Sulfate $(NH_4)_2SO_4$.

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[2] https://byjus.com/chemistry/types-of-solutions/

- ✓ **Insoluble salts** are ionic compounds that do not dissolve significantly in water.
  - When these salts are added to water, they either remain mostly intact as solid crystals or dissolve to a very minimal extent.
  - Examples of common insoluble salts along with their chemical formulas: Barium Sulfate ($BaSO_4$), Lead (II) Sulfate ($PbSO_4$), Silver Chloride (AgCl), Calcium Carbonate ($CaCO_3$), Iron (III) Hydroxide ($Fe(OH)_3$).
- ✓ **Sparingly soluble salts** are salts that have a very low, but not negligible, solubility in water.
  - When they are added to water, only a small amount of the salt dissolves, while most of it remains undissolved as a solid.
  - **Examples of sparingly soluble salts**: Silver chloride (AgCl), Barium sulfate ($BaSO_4$), Calcium carbonate ($CaCO_3$).
- ✓ **Solubility rules**
  - All alkali metal compounds and ammonium ($NH_4^+$) compounds are soluble.
  - Nitrates ($NO_3^-$), acetates ($C_2H_3O_2^-$), and chlorates ($ClO_3^-$) are soluble.
  - Most chlorides ($Cl^-$), bromides ($Br^-$), and iodides ($I^-$) are soluble, except for those of silver ($Ag^+$), lead ($Pb^{2+}$), and mercury ($Hg^{2+}$).
  - Most sulfates ($SO_4^{2-}$) are soluble, with exceptions for barium ($Ba^{2+}$), strontium ($Sr^{2+}$), lead ($Pb^{2+}$), and calcium ($Ca^{2+}$).
  - Most hydroxides ($OH^-$) are insoluble, except for those of alkali metals and barium ($Ba^{2+}$).
  - Most carbonates ($CO_3^{2-}$), phosphates ($PO4^{3-}$), and sulfides ($S^{2-}$) are insoluble, except for those of alkali metals and ammonium ($NH_4^+$).
  - Compounds containing polyatomic ions with alkali metals or ammonium are generally soluble.

- **Identification of factors affecting solubility of salts**
  - ✓ **Temperature**
    - The solubility of most solid substances in liquid solvents increases with increasing temperature.
    - Generally, the solubility of liquids in liquids increases with increasing temperature.

  - Generally, the solubility of gases in liquids decreases as the temperature increases.
- ✓ **Pressure**
  - For majority of solid and liquid solutes, pressure does not affect solubility.
  - As for gasses, the Henry's law states that solubility of gas is directly proportional to the pressure of this gas. This is mathematically presented as **$p = kc$**, where **$k$** is a temperature dependent constant for a gas
- ✓ **Polarity**
  - In most cases, solutes dissolve in solvents that have a similar polarity.
  - Polar solutes tend to dissolve well in polar solvents, and nonpolar solutes tend to dissolve well in nonpolar solvents (**Like dissolves like)**
- ✓ **Molecular size of solute**
  - Generally, smaller molecules tend to dissolve more easily in solvents compared to larger molecules.
  - Smaller molecules can more readily interact with solvent molecules, allowing for effective solvation and dispersion.

    Larger molecules may have more complex structures and greater steric hindrance, which can hinder their ability to interact with solvent molecules

- **Types of solution**

Based on solubility, solutions can be categorized into three types: unsaturated, saturated and supersaturated.

- ✓ **An unsaturated solution** contains less solute than the maximum amount that can dissolve in the solvent at a given temperature and pressure.
  - This type of solution can still dissolve more solute at a given temperature.
  - The solvent hasn't reached its maximum capacity to dissolve the solute
  - An example of an unsaturated solution is a glass of water in which you have added a small amount of table salt (sodium chloride). If you stir the salt into the water and it completely dissolves, the solution is unsaturated because it can still dissolve more salt without any remaining undissolved particles.
- ✓ **A saturated solution** contains the maximum amount of solute that can dissolve in a solvent at a given temperature and pressure.

    - Any additional solute added to a saturated solution will not dissolve and will remain as a solid precipitate.
    - Example is a sugar solution. If you add sugar to hot water, you can dissolve a large amount of sugar. However, if you continue to add sugar until it no longer dissolves and you see undissolved sugar at the bottom, the solution is saturated.
- **A supersaturated solution** contains more solute than what can normally dissolve at a given temperature and pressure.
    - These solutions are unstable and can easily crystallize, causing the excess solute to precipitate out.
    - Supersaturated solutions are often created by heating a saturated solution and then cooling it slowly.
    - Carbonated beverages like soda are a type of supersaturated solution. They contain carbon dioxide gas ($CO_2$) dissolved under high pressure. When the pressure is released (e.g., when opening the bottle), the gas may rapidly come out of solution, forming bubbles. In this case, the solution is supersaturated with $CO_2$.

## Activity 2: Guided Practice

### Task 10:

Mutoni is a student at University of Byumba. She has an unknown salt and tasked with determining whether it is soluble, insoluble, or sparingly soluble in water. The salt contains the following ions: Barium ($Ba^{2+}$), Sulfate ($SO_4^{2-}$). As you are asked to help Mutoni to determine whether the salt is soluble, insoluble, or sparingly soluble in water.

Referring to the above scenario perform the following task

1. Take a 20g of the salt and examine its physical appearance
2. Add a small amount of the salt to a beaker of cold distilled water and stir the mixture.

3. Repeat the solubility test with warm distilled water, stirring to see if more salt dissolves.
4. After attempting to dissolve the salt, check if there is any undissolved residue remaining at the bottom of the beaker.
5. Add excess salt to a beaker of water and stir until no more salt dissolves.
6. Based on the observation conclude the solubility of a given salt

## Activity 3: Application

### Task 11:

Mbabazi boiled water for cooking cornbread. While she went outside his brother started adding salt to boiling water to dissolve it more quickly. As Mbabazi return she kept adding salt to the water and stir until it eventually reached the point where no more salt can dissolve. However, any additional salt remained undissolved at the bottom.

Referring to the scenario above, perform the following tasks

1. Fill a clear glass or beaker with a 100 mL of water
2. Gradually add salt to the water while stirring continuously.
3. Stop adding salt once it completely dissolves.
4. Record the amount of salt added.
5. Discuss why the solution is unsaturated and what would happen if more salt is added.

## Topic 2.2: Solubility product

### Activity 1: Problem Solving

### Task 12:

SIBPHARM is a pharmaceutical company working on developing a new medication in the form of a tablet. The active ingredient is poorly soluble in water, which affects its bioavailability in the body. They need to increase the solubility of the medication to ensure it dissolves properly in the digestive system.

Referring to the scenario above, do the following tasks

1. How can the solubility product constant (Ksp) of the active ingredient be determined?
2. If a salt of the active ingredient is used as a formulation strategy, how will the common ion effect influence solubility?
3. Given the solubility (s) of a poorly soluble compound, how can the concentrations of the dissociated ions be calculated at equilibrium?
4. If the Ksp of a compound is known, how can you calculate the maximum concentration of the active ingredient that will dissolve in the digestive system after ingestion?
5. If the solubility of the active ingredient is given as 0.002 mol/dm$^3$, calculate the solubility product (Ksp) for the compound if it dissociates into two ions (one positive and one negative ion) in solution.
6. Explain how formulation of medication is related to solubility salts

### Key factor 2.2a: Definition of the solubility product

- **Dissociation of sparingly soluble salts in water**
  - ✓ **A dissociation equation** represents the process in which an ionic compound (usually a solid) separates into its ions when it dissolves in a solvent (like water).

- Below are dissociation equations for NaCl, Ca $(NO_3)_2$ , and $(NH_4)_3PO_4$.

$$NaCl_{(s)} \longrightarrow Na^+_{(aq)} + Cl^-_{(aq)}$$

$$Ca(NO_3)_{2(s)} \longrightarrow Ca^{2+}_{(aq)} + NO_3^-{}_{(aq)}$$

$$(NH_4)_3PO_{4.} \longrightarrow 3NH_4^+{}_{(aq)} + PO_4^{3-}{}_{(aq)}$$

- **Expression of solubility product (*K*sp)**
  - ✓ **The solubility product,** denoted as **(*K*sp)**, is an equilibrium constant that describes the solubility of a sparingly soluble ionic compound in water.
    - It is the product of the concentrations of the ions involved in the dissolution, each raised to the power of its stoichiometric coefficient in the balanced dissolution equation.
    - Consider the general dissolution reaction below (in aqueous solutions):

$$aA_{(s)} \longrightarrow cC_{(aq)} + d\,D_{(aq)}$$

- To solve for the **Ksp** it is necessary to take the molarities or concentrations of the products ( **cC** and **dD** ) and multiply them.
- If there are coefficients in front of any of the products, it is necessary to raise the product to that coefficient power (and also multiply the concentration by that coefficient). This is shown below:

**Ksp = $[C]^c[D]^d$**

- Note that the reactant, **aA,** is not included in the **Ksp** equation. Solids are not included when calculating equilibrium constant expressions**.**
- **Examples of** expression of Ksp for some compounds

**i)** $$AgCl_{(s)} \longrightarrow Ag^+_{(aq)} + Cl^-_{(aq)}$$

**Ksp of AgCl =** [Ag+] [Cl-]

ii) Solubility product for lead II sulphate ($PbSO_4$)

$$PbSO_{4(aq)} \longrightarrow Pb^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)}$$

**Ksp** = **$[Pb^{2+}]$ $[SO_4^{2-}]$**

iii) Solubility product for lead II iodide ($PbI_2$)

$$PbI_{2(s)} \longrightarrow Pb^{2+}_{(aq)} + 2I^{-}_{(aq)}$$

**Ksp** = **$[Pb^{2+}][I^{-}]^2$**

iv) Solubility product for $MgF_2$

$$MgCl_{2(s)} \longrightarrow Mg^{2+}_{(aq)} + 2F^{-}_{(aq)}$$

**Ksp = $[Mg^{2+}][F^{-}]^2$**

## Key Facts 2.2b: Calculation of the solubility product

- **Relationship between solubility and solubility product**
  - ✓ **Solubility equilibrium** refers to kind of equilibrium that exists in saturated solutions of sparingly soluble ionic salts. Solubility is normally expressed in moldm$^{-3}$ or (gdm$^{-3}$).
    - Solubility describes the dissolution of a substance in a solvent
    - Solubility product describes the mathematical product of the dissolved ion concentrations raised to the power of their stoichiometric coefficients.
    - The solubility can be denoted by using‘s’ and solubility product is expressed by Ksp
  - ✓ **Consider the following reaction**

$$A_nB_{m(s)} \longrightarrow mB^{n-}_{(aq)} + nA^{m+}_{(aq)}$$

The ksp expression is as follow **Ksp = $[A^{m+}]^n[B^{n-}]^m$**

**Suppose** $[A_nB_m] = s$ Therefore, $[A^{m+}] = ns$ and $[B^{n-}] = ms$

Replace these values in Ksp expression thus Ksp= $(ns)^n(ms)^m$

Ksp= $n^n m^m s^n s^m$

Ksp= $n^n m^m s^{n+m}$

$s^{n+m} = \frac{Ksp}{n^n m^m}$

$s = \sqrt[m+n]{\frac{Ksp}{n^n m^m}}$

- **Calculation of solubility products from solubility**
  - ✓ **Steps to Calculate Ksp from Solubility**
    - Write the balanced dissolution equation

- Determine the ion concentrations in terms of solubility by multiplying the stoichiometric coefficiency of each ion to the concentration of the salts
- Write the Ksp expression
- Substitute the concentrations in terms of s and solve for Ksp

✓ **Worked examples:**

1. The solubility of calcium carbonate $CaCO_3$, at 298K is $6.9\times10^{-3}$ $moldm^{-3}$. Calculate the solubility product at this temperature.

**Solution**

**The dissociation equation is as follow**

$$CaCO_{3(s)} \longrightarrow Ca^{2+}_{(aq)} + CO_3^{2-}{}_{(aq)}$$

**The ksp expression** $Ksp = [Ca^{2+}][CO_3^{2-}]$

**Calculation of concentration of each ion**

From the equation 1 mole of $CaCO_3$ dissociate to give 1 moles of $Ca^{2+}$ and 1 mole of $CO_3^{2-}$ since the ratio is 1:1

**$[Ca^{2+}] = [CaCO_3]$** Therefore, **$[Ca^{2+}]$**$= 6.9\times10^{-3}$ $moldm^{-3}$

**$[CO_3^{2-}] = [CaCO_3]$** Therefore, **$[CO_3^{2-}]$** $= 6.9\times10^{-3}$ $moldm^{-3}$

**Replace this value in Ksp expression**

**$Ksp = [Ca^{2+}][CO_3^{2-}]$** $= (6.9\times10^{-3}\ moldm_3)^2$ **$= 4.8\times10\text{-}9mol^2dm^{-6}$**

2. The solubility of calcium sulphate $CaSO_4$ at 298K is $0.67g/dm^3$. Calculate the solubility product at this temperature. (O=16, S=32, Ca=40)

**Solution.**

**The dissociation equation for $CaSO_4$ is as follow**

$$CaSO_{4(s)} \longrightarrow Ca^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)}$$

**Convert the solubility from $g/dm^3$ to $mol/dm^3$** by dividing the given solubility by the molar mass of $CaSO_4$

**The molar mass of** $CaSO_4$= (40g/mol) + (32g/mol) + (16g/mol X 4) = 136g/mol

Therefore, the solubility in **$mol/dm^3$**$=\frac{0.67g/dm^3}{136g/mol} = 4.93\times10^{-3}\ mol/dm^3$

From the chemical equation **1** mole of calcium sulphate dissolves to produce **1** mole of $Ca^{2+}$ ions and **1** mole of **$SO_4^{2-}$** ions in solution.

**$[Ca^{2+}]$** = $4.93\times10^{-3}$ mol/dm$^3$

**$[SO_4^{2-}]$** = $4.93\times10^{-3}$ mol/dm$^3$

**Ksp = $[Ca^{2+}][SO_4^{2-}]$** Ksp = $(4.93\times10^{-3})^2$ = **$2.4 \times 10^{-5}$ mol$^2$dm$^{-6}$**

3. The solubility of lead II chloride, $PbCl_2$ is 0.016mol/dm$^3$ at 298k. Calculate the solubility product at this temperature.

   **Solution**

   **The dissociation equation is as follow**

   $PbCl_{2(s)} \longrightarrow Pb^{2+}{}_{(aq)} + 2Cl^-{}_{(aq)}$

   The ksp is expressed as follow **Ksp = $[Pb^{2+}][Cl^-]^2$**

   The ratio of the ions in the compound is **1:2;** each mole of **lead (II) chloride** produces **1mole** of **lead II**, and **2 moles** of **chloride ions** in solution

   $[Pb^{2+}]$ = 0.016 moldm$^{-3}$**.**

   $[Cl^-]$ = 0.016×2= **0.032 mol/dm$^3$**

   **Replace this value in ksp expression**

   ksp= $0.016\times(0.032)^2$ = **$1.6\times10^{-5}$mol$^3$dm$^{-9}$**

4. The solubility of calcium phosphate, $Ca_3(PO_4)_2$ is $7.7\times 10^{-4}$g/dm$^3$ at 25$^0$c. Calculate the solubility product at this temperature. (O =16, P =31, Ca=40).

   **Solution**

   **The dissociation equation is as follow**

   $Ca_3(PO_4)_{2(s)} \longleftrightarrow 3\,Ca^{2+}(aq) + 2PO_4^{3-}\,(aq)$

   **Key points:**

   **Convert the concentration in g/dm$^3$** to **mol/dm$^3$**

   Number of moles = $\frac{solubility\ in\ g/dm^3}{molar\ mass}$

   molar mass of $Ca_3(PO_4)_2$= (40g/mol x 3)+ (31g/molx2)+ (16g/mol x4x2)= **310g/mol**

   **Concentration in moldm$^{-3}$** = $\frac{7.7\times10^{-4} g/dm^3}{310\text{g/mol}}$/310 = **$2.48\times10^{-6}$mol/dm$^3$**

   Each **mole** of calcium phosphate that dissolves produces **3 moles** of calcium ions in solution and **2 moles** of phosphate ions. therefore

   **$[Ca^{2+}]$= $3\times2.48\times10^{-6}$** = $7.44\times10^{-6}$mol/dm$^3$

**$[PO_4^{3-}]$**= $2\times2.48\times10^{-6}=4.96\times10^{-6}$ mol/dm$^3$ **Ksp = $[Ca^{2+}]^3[PO_4^{3-}]^2$ = $(7.44\times10^{-6})^3\times(4.96\times10\text{-}6)^2$ = $1.0\times10^{-26}$mol$^5$dm$^{-15}$.**

- **Calculating solubility from solubility product**
  - ✓ **Steps to calculate the solubility from the solubility product**
    - Write the Balanced Dissolution Equation
    - Write the Ksp Expression
    - Express the ion concentrations in terms of 's' based on the stoichiometry of the dissolution equation.
    - Replace the ion concentrations in the Ksp expression with their 's' equivalents
    - Rearrange the equation to isolate 's' and solve for its value.
    - Substitute the given Ksp value into the equation and calculate the value of 's'.
  - ✓ **Worked examples**

1. Calculate the solubility in mol/dm$^3$ of silver chloride, AgCl, at 298K if its solubility product is $1.8\times10^{-10}$ mol$^2$dm$^{-6}$

**Solution**

$AgCl_{(s)} \longleftrightarrow Ag^+_{(aq)} + Cl^-_{(aq)}$

**Key points**

For every mole of silver chloride that dissolves, the solution will contain 1 mole of $Ag^+_{(aq)}$ and 1 mole of $Cl^-_{(aq)}$ so if **"s"** moles dissolved, the solution will contain **"s"** moles of each ion.

$[Ag^+]$= **s** moldm$^{-3}$

$[Cl^-]$= **s** moldm$^{-3}$

**Ksp = $[Ag^+][Cl^-]$** hence **$1.8\times10^{-10}$ = s x s** and s=$\sqrt{\mathbf{1.8\times10^{-10}}}$

**2.** Calculate the solubility in gdm-3 of chromium III hydroxide, $Cr(OH)_3$ at 25$^0$C if its solubility product is $1.0\times10^{-33}$mol$^4$ dm$^{-12}$ (H=1, O=16,Cr=52)

**Solution**

$Cr(OH)_3\ (s) \longleftrightarrow Cr^{3+}_{(aq)} + 3OH^-_{(aq)}$

Work out the solubility in moldm$^{-3}$

Number of moles = mass (g)/ molar mass (g)

**1mole** of $Cr(OH)_3$ produces **1 mole** of $Cr^{3+}$(aq) and **3 moles** of $OH^-$ ions

**$[Cr^{3+}]$**= S moldm$^{-3}$

$[OH^-]$= 3S $moldm^{-3}$

**Ksp = $[Cr^{3+}][OH^-]^3$** = $1.0\times10^{-33}$=**$S\times(3S)^3$**

**S** = $27S^4$= $1.0\times10^{-33}$

**S= $2.47\times10^{-9}$$moldm^{-3}$**

## Key factor 2.2c. Application of solubility

- ✓ **Pharmaceuticals:** Medications are often formulated to enhance solubility, ensuring they dissolve properly in the body to be effective.
- ✓ **Environmental Science:** It helps in assessing the movement and impact of substances like pesticides or heavy metals in aquatic systems.
- ✓ **Food Industry**: In food processing, solubility affects flavor, texture, and preservation.
- ✓ **Chemical Engineering:** Solubility is essential in designing and optimizing processes such as extraction, crystallization, and formulation of products.
- ✓ **Cosmetics:** In the formulation of skincare and beauty products, solubility determines how well active ingredients dissolve and interact with the skin, impacting the product's effectiveness.
- ✓ **Agriculture:** The solubility of fertilizers affects how they are applied to plants. Soluble fertilizers provide essential nutrients more readily to plants, enhancing growth and yield.
- ✓ **Biology:** It is important in understanding how substances interact within living organisms.
- ✓ **Materials Science:** Solubility is relevant in developing materials with specific properties, such as polymers or composites, where dissolving and blending different substances can create desired characteristics.

## Activity 2: Guided Practice

### Task 13:

Muhire is a chemist working in a laboratory, and he need to calculate the solubility product (Ksp) of a sparingly soluble salt, calcium carbonate ($CaCO_3$). The solubility of $CaCO_3$ at 298 K is given as $6.9 \times 10^{-3}$ mol/dm$^3$. Help Muhire to calculate the Ksp of $CaCO_3$ at this temperature

Referring to the above scenario perform the following task

1. Write the dissociation equation for $CaCO_3$
2. Determine the ion concentrations in terms of solubility by multiplying the stoichiometric coefficient of each ion to the concentration of the salt.
3. Write the Ksp expression for $CaCO_3$
4. Substitute the concentrations in terms of s and solve for Ksp

## Activity 3: Application

### Task 14:

Rwema is a researcher working in a pharmaceutical company, and he need to calculate the solubility of silver chloride (AgCl) at 298 K. The solubility product (Ksp) of AgCl is given as $1.8 \times 10^{-10}$ mol$^2$/dm$^6$. Help him to calculate the solubility of AgCl at this temperature.

Referring to the above scenario do the following task

1. Write the dissociation equation for AgCl.
2. Express the ion concentrations in terms of 's' based on the stoichiometry of the dissolution equation.
3. Write the Ksp expression for AgCl.
4. Rearrange the equation to isolate 's' and solve for its value.
5. Substitute the given Ksp value into the equation and calculate the value of 's'.

## Formative Assessment

1. A chemistry class is comparing the solubility of two salts: sodium chloride (NaCl) and calcium chloride ($CaCl_2$).
2. They notice that NaCl is more soluble in water than $CaCl_2$.

a) Which of the following salts is more soluble in water?

   i) Sodium chloride (NaCl)
   ii) Calcium chloride ($CaCl_2$)
   iii) Both have equal solubility
   iv) Neither is soluble in water

b) What is the likely reason for the difference in solubility between NaCl and $CaCl_2$?

   i) NaCl has a higher molecular weight.
   ii) $CaCl_2$ has a higher molecular weight.
   iii) NaCl has a higher lattice energy.
   iv) $CaCl_2$ has a higher lattice energy

c) Which of the following factors

d) could potentially increase the solubility of $CaCl_2$ in water?

   i) Decreasing the temperature.
   ii) Increasing the pressure.
   iii) Adding more water.
   iv) All of the above.

3. NaCl is mixed with 100ml water in three beakers according to the following ratios; first beaker adds 30g, 40g and 60g in second and third beaker respectively and relate findings with type of solution.

a) When 30g of NaCl is added to 100ml of water, the solution is most likely:

   i) Unsaturated
   ii) Saturated
   iii) Supersaturated
   iv) Cannot be determined

b) When 40g of NaCl is added to 100ml of water, the solution is most likely:

   i) Unsaturated

   - ii) Saturated
   - iii) Supersaturated
   - iv) Cannot be determined

c) When 60g of NaCl is added to 100ml of water, the solution is most likely:
   - i) Unsaturated
   - ii) Saturated
   - iii) Supersaturated
   - iv) Cannot be determined

d) Which of the following is a saturated solution?
   - i) A solution where no more solute can be dissolved at a given temperature.
   - ii) A solution where more solute can be dissolved at a given temperature.
   - iii) A solution that contains less solute than the maximum amount that can dissolve.
   - iv) None of the above.

e) A supersaturated solution is formed by:
   - i) Adding more solute to a saturated solution.
   - ii) Cooling a saturated solution.
   - iii) Heating a saturated solution and then cooling it slowly.
   - iv) All of the above.

4. Students are working in a laboratory, and your task is to investigate how different factors influence the solubility of a variety of substances. They have access to four main substances: sugar ($C_6H_{12}O_6$), salt (NaCl), carbon dioxide ($CO_2$), and oil (vegetable oil). From the given information answer the following questions by **True** or **False**
   a) Salt (NaCl) dissolves in non-polar solvents like vegetable oil
   b) Carbon dioxide ($CO_2$) is more soluble in water at higher temperatures
   c) Vegetable oil is soluble in water due to its non-polar nature
   d) Sugar will dissolve faster in warm water compared to cold water because solubility increases with temperature.
   e) The solubility of NaCl in water is unaffected by changes in pressure.
5. A chemist is trying to dissolve a non-polar organic compound in water. Why is the compound not dissolving?
6. A soda can is opened. Explain why does the carbon dioxide fizz out?

7. A chemist needs to dissolve a large amount of a solid salt in water. How can they increase the solubility of the salt?
8. You are conducting an experiment where you need to dissolve a salt (like potassium nitrate) in water. You have two beakers, one filled with cold water (5°C) and the other with hot water (60°C).
   a) Which beaker, the one with cold water or the one with hot water, do you think will dissolve more potassium nitrate? Why?
   b) What other factors, besides temperature, might affect the solubility of a salt in water?
9. Students are comparing the solubility of two salts, sodium chloride (NaCl) and sugar (sucrose), in water. Both salts have similar polarities, but sucrose molecules are much larger than NaCl molecules. Predict will be more soluble in water? Why?
10. You're a beverage chemist tasked with creating a new, refreshing drink. You have a variety of ingredients, including sugars, flavorings, and carbonated water.
    a) How does temperature affect the solubility of sugars in water?
    b) How does pressure affect the solubility of carbon dioxide gas in water?
    c) Why do smaller molecules typically dissolve more easily in solvents compared to larger molecules?
    d) What happens to the solubility of carbon dioxide ($CO_2$) in water when the temperature is increased?
11. You are tasked with creating a new cleaning product. The goal is to dissolve vegetable oil (nonpolar) in a liquid solvent; water (polar), Hexane (nonpolar). Which one will dissolve vegetable oil effectively?
12. A student adds a spoonful of salt to a glass of water and stirs. The salt seems to disappear.
    a) Explain what happened to the salt.
    b) Relate the terms solute, solvent, and solution in this context.
13. You are given a small amount of Calcium Carbonate ($CaCO_3$) and asked to dissolve it in water. After adding it to a beaker of water, you observe that only a small amount of the salt dissolves, and most of it remains as solid particles at the bottom.
    a) Why does Calcium Carbonate ($CaCO_3$) not dissolve completely in water?
    b) What does the term "sparingly soluble" mean in this context?
14. Maliza is preparing saltwater solutions for a chemistry lab. She is using two beakers with equal amounts of salt (NaCl), but you change the conditions: Beaker 1: Cold water (5°C),

Beaker 2: Hot water (60°C). Why would hot water (70°C) dissolve sugar more quickly than cold water (5°C)?

15. Explain why does a carbonated drink go flat faster when it's warm?
16. A carbonated beverage loses its fizz over time, even when the bottle is tightly sealed. Explain why this happens, referencing factors affecting gas solubility.
17. You have been given the following salts: Sodium Chloride ($NaCl$), Barium Sulfate ($BaSO_4$), Silver Chloride ($AgCl$), Potassium Nitrate ($KNO_3$), Calcium Carbonate ($CaCO_3$), Magnesium Sulfate ($MgSO_4$). Classify each salt as soluble, insoluble, or sparingly soluble based on your knowledge of solubility rules.
18. The solubility of silver chromate, $Ag_2CrO_4$, is $1.3 \times 10^{-4}$ mol/dm$^3$. Calculate its solubility product, Ksp.
    a) Write the balanced dissociation equation for $Ag_2CrO_4$
    b) Determine the concentration of ions in terms of s
    c) Write the Ksp expression
    d) Calculate Ksp
19. The solubility product of lead(II) iodide, $PbI_2$, is $1.4 \times 10^{-8}$ mol$^3$/dm$^9$. Calculate its solubility in g/dm$^3$. (Atomic masses: Pb = 207, I = 127).
    a) Write the balanced dissociation equation for $PbI_2$
    b) Determine the concentration of ions in terms of s
    c) Write the Ksp expression of $PbI_2$
    d) Calculate Ksp of $PbI_2$

## Points to Remember

- ✓ Solubility is the ability of a salute to dissolve in a solvent.
- ✓ Solutions can be categorized as unsaturated, saturated, and supersaturated.
- ✓ Factors include temperature (most solids dissolve better at higher temperatures), pressure (affects gas solubility), polarity (like dissolves like), and molecular size (smaller molecules generally dissolve more easily).
- ✓ When soluble salts dissolve in water, they dissociate into their constituent ions.
- ✓ To calculate Ksp from solubility, write the balanced dissolution equation, express ion concentrations in terms of solubility, and substitute into the Ksp expression.
- ✓ The solubility can be calculated from the following equation **s =** $\sqrt[m+n]{\frac{Ksp}{n^n m^m}}$

## Self-Reflection

1. Fill in and complete the self-assessment table below to assess your level of knowledge, skills and attitudes after covering this unit.
2. There are no right or wrong ways to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.
3. Think about yourself:
    a. Do you think that you have knowledge, skills or attitudes to do the tasks?
    b. How well?
4. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills and attitudes.

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Relate qualitative and quantitative analysis to know the composition of any sample | | | | | |
| Explain the change in factors that would help to know the quality of a sample | | | | | |
| Differentiate qualitative and quantitative analysis | | | | | |
| Distinguish inorganic and organic qualitative analysis | | | | | |
| Identify the methods for qualitative and quantitative analysis | | | | | |
| Explain the principle behind each qualitative method | | | | | |
| Demonstrate the ability to analyze and interpret the chemical | | | | | |

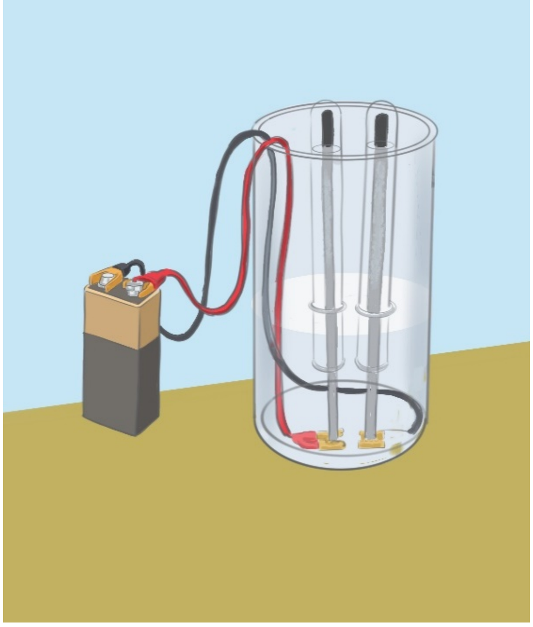
| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| composition of samples | | | | | |
| Recognize the quantitative methods of analysis | | | | | |
| Identify the basic principles of stoichiometry | | | | | |
| Identify the change in factors that would help to know the amount of substance | | | | | |
| Select appropriate analytical methods based on sample properties, desired sensitivity, and selectivity | | | | | |
| Integrate qualitative and quantitative data to provide a comprehensive understanding of a sample | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Clearly present qualitative and quantitative findings | | | | | |
| Evaluate the effectiveness of different qualitative and quantitative methods | | | | | |
| Explain the application of chemical analysis | | | | | |

5. Fill in the table above and share results with the trainer for further guidance.

| Areas of strength | Areas for improvement | Actions to be taken to improve |
|---|---|---|
| **1.**<br>**2.**<br>**3.** | **1.**<br>**2.**<br>**3.** | **1.**<br>**2.**<br>**3.** |

# UNIT 3: DESCRIBE THE ELECTROCHEMICAL CELL REACTIONS



## Unit summary

This unit provides you with the knowledge, skills and attitudes required to describe electrochemical cells by explaining electrolysis, illustrate the galvanic cell and determination of electromotive force of the cell.

## Self-Assessment: Unit 3

1. Referring to the unit illustrations above discuss the following:
    b. What do the illustrations show?
    c. What is the difference between the different images in the illustration?
    d. What do you think this unit is about based on the illustration?
2. Fill in and complete the self-assessment table below to assess your level of knowledge, skills, and attitudes under this unit.
    a. There is no right or wrong way to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.
    b. Think about yourself: do you think you have the knowledge, skills or attitudes to do the task? How well?
    c. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills, and attitudes.
    d. At the end of this unit, you will assess yourself again.

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Explain the basic concepts of electrochemistry, such as oxidation, reduction, and redox reactions. | | | | | |
| Describe the process of electrolysis | | | | | |

| My experience | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| **Knowledge, skills and attitudes** | | | | | |
| Explain Faraday's first and second laws of electrolysis | | | | | |
| Identify the structure and function of galvanic (voltaic) cells | | | | | |
| Differentiate between galvanic (voltaic) and electrolytic cell | | | | | |
| Recognize the types of redox reactions | | | | | |
| Explain the concept of standard electrode potential | | | | | |
| Describe how to calculate and interpret the overall EMF of a cell | | | | | |
| Interpret the diagram of an electrochemical cell | | | | | |
| Differentiate primary and secondary cells | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Recognize the industrial applications of electrolysis, | | | | | |

## Key Competencies:

| Knowledge | Skills | Attitudes |
|---|---|---|
| 1. Explain the basic concepts of electrochemistry, such as oxidation, reduction, and redox reactions. | 1. Calculate the oxidation state atoms in redox reaction and identify the oxidation or reduction reaction | 1. Paying close attention to the rules and guidelines for assigning oxidation numbers to different elements and compounds |
| 2. Describe the process of electrolysis | 2. Conducting basic electrolysis experiments such as electrolysis of water | 2. Prioritizing safety while conducting electrolysis experiment |
| 3. Explain Faraday's first and second laws of electrolysis | 3. Use Faraday's laws to calculate the amount of substance liberated at electrodes during electrolysis. | 3. Pay close attention to units and throughout the calculations. |
| 4. Recognize the industrial applications of electrolysis | 4. Draw the electrolytic cell indicating the application of electrolysis and identify the reaction occurred | 4. Be receptive to explore different types of electrolysis applications |

| Knowledge | Skills | Attitudes |
|---|---|---|
| 5. Describe the structure and function of galvanic (voltaic) cells | 5. Illustrate the general representation of galvanic cell | 5. Have willingness to consider new ideas about galvanic cell |
| 6. Differentiate between galvanic (voltaic) and electrolytic cell | 6. Representing electrochemical cells graphically, including electrodes, electrolytes, and electron flow | 6. Persisting through the process of drawing and refining the diagram until it accurately represents the desired cell. |
| 7. Differentiate primary and secondary cells | 7. Identify various battery and classifying them as primary or secondary. | 7. Have a strong interest in learning about different types of batteries and their characteristics. |
| 8. Explain the concept of standard electrode potential | 8. Predict which electrode will undergo reduction or oxidation in a redox reaction by using standard electrode potentials | 8. Pay close attention to the signs and magnitudes of the standard reduction potentials. |
| 9. Describe how to calculate and interpret the overall EMF of a cell | 9. Calculating cell potential (EMF) using standard electrode potentials. | 9. Persisting through challenging calculations and not giving up easily when encountering difficulties. |
| 10. Interpret the diagram of an electrochemical cell | 10. Writing the cell notation used to represent the electrochemical cell diagram | 10. Striving for clear and precise notation that can easily be interpreted by others. |

## Discovery activity:

### Task 15:

1. While you are at school observe the following materials; dry cells used as a source of power in various radios, lithium-ion batteries used in mobile phones, old coins, rusted iron sheets, and old rings or jewelry from your parent.
2. Moreover, watch the video of the electrolysis of NaCl and answer the following questions by referring to your understanding of electrochemical cells.

After observing the presented materials and video, discuss the following:

a. Why does an old coin change its color or appearance over time?
b. Is the corrosion or tarnishing of a coin an example of an oxidation reaction?
c. How the dry cell differs from the lithium-ion battery
d. Describe the process of electrolysis
e. Identify and explain the roles of the two main components of an electrolytic cell
f. Can electrolysis be used to remove rust from an iron sheet?
g. Describe how cations and anions move towards the cathode and anode, respectively,
h. What are the functions of the anode and cathode in an electrolytic cell?
i. Can you explain why sodium metal is collected at the cathode in the electrolysis of NaCl?
j. Can you classify the dry cell and lithium-ion battery into primary and secondary cell?

# Topic 3.1: Electrolysis

## Activity 1: Problem Solving

### Task 16:

Mugisha has a container filled with saltwater (a simple solution of sodium chloride dissolved in water), and he want to use electrolysis to split the solution into different useful substances. He tried to introduce electric current through the saltwater to decompose the sodium chloride into sodium hydroxide (NaOH) and chlorine gas ($Cl_2$), both of which play important roles in soap-making.

Referring to the scenario above, answer to the following tasks

1. What equipment and materials do Mugisha need to set up an electrolysis experiment with salt water?
2. What safety precautions should Mugisha take when performing electrolysis on salt water?
3. What is required to initiate electrolysis in a saltwater solution?
4. What roles do the anode and cathode play in the electrolysis of saltwater?
5. What is the chemical formula for sodium chloride, and what ions does it dissociate into when dissolved in water

## Key Facts 3.1 Explanation of electrolysis

- **Introduction to electrolysis**

| Electrochemistry | Electrolysis |
|---|---|
| Is the branch of chemistry that deals with the relationship between electrical energy and chemical change. These are chemical processes that cause electrons to move | Is a chemical process in which electrical energy is used to drive a non-spontaneous chemical reaction. In electrolysis the ionic substances are decomposed (broken down) into simpler substances when an electric current is passed through them. |

| Electrochemical cell | Redox reactions |
|---|---|
| Is a device, which is capable of either producing electrical energy from chemical reactions or causing chemical reactions to take place through the | **Reduction-oxidation** reactions are chemical reactions that involve the transfer of electrons between two substances.<br>○ **A reduction reaction** is a type of chemical reaction where a substance gains electrons, resulting in a decrease in its oxidation state. |

| | |
|---|---|
| introduction of electrical energy.<br>○ There are two types of electrochemical cells: **galvanic (voltaic)** cells and **electrolytic cells**. | ○ **An oxidation reaction** is a type of chemical reaction in which a substance loses electrons, increasing in its oxidation state. |

✓ **Spontaneous and non-spontaneous reaction**

| Spontaneous reactions | Non-spontaneous reactions |
|---|---|
| These are chemical reactions that occur naturally under specific conditions without the need for external energy input. | These are chemical reactions that do not occur naturally under standard conditions and require an input of energy to proceed**.** |

✓ **Electrolytic cell**

An electrolytic cell is an electrochemical cell that requires an external source of electrical energy (voltage applied between two electrodes) to drive a chemical reaction that would not otherwise occur.

**Components of electrolytic cells**

- There are two main components of electrolytic cells; **electrodes** and **electrolyte**

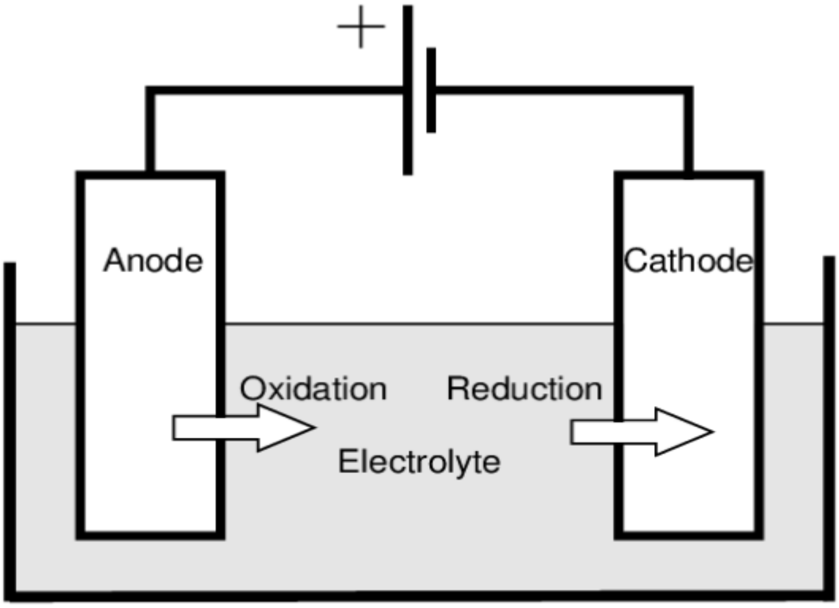
1. **Electrodes**: are solids electric conductors that carry electric current into non-metallic solids, or liquids, or gases, or plasmas, or vacuums.

- Electrodes are typically good electric conductors, but they need not be metals.
- Electrode used in electrolysis are **anode** or **cathode**
  a. **The Anode** is the positive electrode where the oxidation reaction occurs during electrolysis.
  b. **The Cathode** is the negative electrode where a reduction reaction occurs during electrolysis.

2. **The Electrolyte**: a substance that, in solution or when molten, ionizes and conducts electricity.

- When electric current passes through electrolyte is ionized and its ion are transported toward cathode and anode of a cell.
- Electrolyte can either be **strong or weak electrolyte** depending on its level of ionization.
  a. **A strong electrolyte** is a solution/solute that completely, or almost completely, ionizes or dissociates in a solution.
- Strong electrolytes fall into three categories: strong acids, strong bases, and salts. (Salts are sometimes also called ionic compounds,
  b. **A weak electrolyte** is an electrolyte that does not completely dissociate in aqueous solution. Weak electrolytes are only partially ionized.
- The weak electrolytes include weak acids and weak bases.

**Diagram of electrolytic cell**



[3]

*Figure 4 Diagram of electrolytic cell*

**Working principle of an electrolytic cell**

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[3] https://www.researchgate.net/figure/Schematic-diagram-of-a-simple-electrolytic-cell-Arrows-indicate-the-motion-of-ions_fig2_347841630

- When an electric current is passed into the circuit, the cathode becomes rich in electrons and develops a negative charge.
- The positively charged ion (cations) are now attracted towards the negatively charged cathode.
- Simultaneously, the negatively charged ions are attracted to the positively charged anode.
- CCC = Cathode Collects Cations. Anode is the site of oxidation, or,
- AAA = Anode Attracts Anions.

- **Faraday's law of electrolysis**
  - **Faraday's first law**

According to this law, "**The amount of substance liberated at an electrode is directly proportional to the quantity of electricity passed**".

**Or**

Where **M** = amount of substance liberated in gram. **Q** = quantity of electricity passed in Coulomb. Since **Q = I.t**

Where **I =** Current in Ampere and **t =** time in seconds

Hence

Where **Z =** proportionality constant, called electrochemical equivalent.

If I = 1 ampere and t = 1 second then Z = M. Therefore, electrochemical equivalent may be defined as, "The mass of substance (in grams) liberated at the electrode on passing current of 1 ampere for 1 second or on passing 1 coulomb of electricity is called electrochemical equivalent of the substance".

**1F = 96500 coulomb**

So, 1 Faraday [96500 coulomb] of electricity will produce 1 gm equivalent of Ag, Cu and Al at cathode.

**Worked example:** Calculate the amount of electric charge in coulombs which can deposit 5.2g of aluminium when a current was passed through a solution of aluminium sulphate for some time.

**Solution:**

$Al^{3+} + 3e^- \longrightarrow Al_{(s)}$

**3 moles** of electrons are needed to deposit **1 mole** of aluminium (24g of aluminium) 1g of aluminium is deposited by $\frac{\mathbf{3}}{\mathbf{24}}$ moles of electrons 5.2g are deposited by $\frac{\mathbf{3x\ 5.2}}{\mathbf{24}}$moles of electrons

Number of coulombs required = $\frac{\mathbf{3x\ 5.2}}{\mathbf{24}}\boldsymbol{x9500}$ **C** = 62725**C**

- **Faraday's second law**

The quantities of different substances liberated or deposited by the same quantity of electric charge passing through an electrolyte are proportional to their equivalent weights.

$\frac{M_1}{E_1} = \frac{M_2}{E_2}$ Where: **M₁**and **M₂**= masses of different substances liberated or deposited while **E₂** and **E₂** = equivalent weights of these substances.

The equivalent weight (E) of a substance in electrolysis is defined as the weight of the substance that would be deposited or liberated by the passage of one mole of electrons (or one Faraday of charge). It depends on the substance's chemical reactivity and the number of electrons involved in the reaction.

**Worked example:** Suppose you electrolyze a solution of copper (II) sulfate ($CuSO_4$) and a solution of silver nitrate ($AgNO_3$) with the same quantity of electric charge. If 10 grams of copper are deposited at the cathode from the copper (II) sulfate solution, how much silver (in grams) will be deposited from the silver nitrate solution under the same conditions?

**Solution**:

1. **Determine the Equivalent Weights**:

Atomic weight of copper (Cu) = 63.5 g/mol

Copper ions ($Cu^{2+}$) gain 2 electrons to form copper metal, so the equivalent weight of copper is:

$E_{Cu}= \frac{Atomic\ weight}{Number\ of\ electrons} = \frac{63.5}{2}$ = 31.75 g/equiv

Atomic weight of silver (Ag) = 107.9 g/mol

Silver ions ($Ag^+$) gain 1 electron to form silver metal, so the equivalent weight of silver is:

$E_{Ag}= \frac{Atomic\ weight}{Number\ of\ electrons} = \frac{107.9}{1}$ = 107.9 g/equiv

**By using Faraday's second law of electrolysis**

$\frac{m_{Cu}}{E_{Cu}} = \frac{m_{Ag}}{E_{Ag}}$ where $m_{Cu}$ and $m_{Ag}$ are the masses of copper and silver deposited, and $E_{Cu}$ and $E_{Ag}$ are their equivalent weights.

**Substitute Known Values**:

$m_{Cu}$= 10g

$E_{Cu}$= 31.75g/Equiv

$E_{Ag}$= 107.9g/equiv

**Set up the proportion**

$\frac{10}{31.75} = \frac{m_{Ag}}{107.9}$ therefore, $m_{Ag} = \frac{10x107.9}{31.75}$ thus $\boldsymbol{m_{Ag}} = \mathbf{33.96g}$

So, under the same quantity of electric charge, approximately 34 grams of silver will be deposited from the silver nitrate solution.

### ✓ Applications of electrolysis

Electrolysis found a wide application in our daily life including; production of chemicals electroplating, electrometallurgy (metal extraction), Metal refining (Purification)

#### Production of chemicals

Many chemicals, such as **caustic soda, chlorine, potassium permanganate**, **ammonium per-sulphate, hydrogen and oxygen etc**. are produced by electrolysis on a large scale.

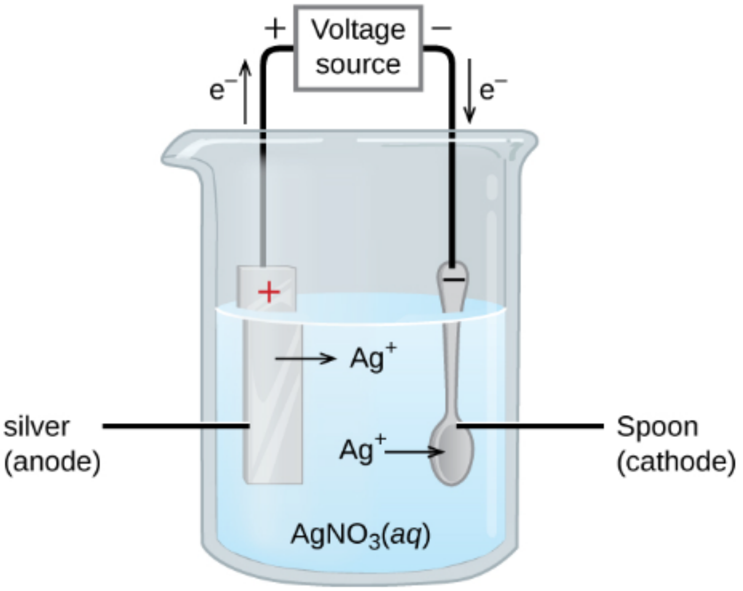
#### Electroplating

This is a process of coating a metal with another of interest mainly to prevent it from rusting, or/ and to improve its appearance,

**For example**, coating a spoon by silver

- The metal being coated is made the cathode and the metal coating is the anode

- The solution used is made of the ions of a metal that is coating, so that the anode can dissolve.
- The anode is pure silver. When direct current passes, the following reactions occur.
- **At cathode**: $Ag^+_{(aq)} + e^- \xrightarrow{\qquad} Ag_{(s)}$ (silver deposits)
- At anode: $Ag_{(s)} \xrightarrow{\qquad} Ag^+_{(aq)} + e^-$ ( silver dissolves)



[4]

*Figure 5 Electroplating of Iron spoon by pure Silver*

A good electroplating requires steady electric current, appropriate concentration of electrolyte and temperature. The metal to electroplate must be clean.

### Electrometallurgy (metal extraction)

Metals in group I and II of the periodic table cannot be reduced by chemical reducing agents; they are extracted from their fused halides by electrolysis.

Sodium is obtained by electrolysis of molten sodium chloride in the Dawncell. Magnesium is obtained by electrolysis of $MgCl_2$, generated from dolomite and seawater.

### Metal refining (Purification)

Metals such as **copper, zinc** and **aluminium** can be purified by electrolysis. The purification of metals is known as **refining**.

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[4] https://wisc.pb.unizin.org/chem109fall2021ver02/chapter/electroplating/

The copper obtained after the reduction process is not very pure. It contains small amounts of impurities such as iron. This copper is called blister copper and is refined by an electrolytic method. It is cast into bars, which are used as anodes in acidified copper (II) sulphate solution.

The cathode is made of thin pure copper. During the electrolysis, $Cu^{2+}$ ions are transferred from the anode to the cathode where they are discharged and copper is deposited.

**At the anode:** $Cu_{(s)} \xrightarrow{\qquad} Cu^{2+}{}_{(aq)} + 2e^-$ **impure copper**

**At the cathode**: $Cu^{2+}{}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$ **pure copper**

The net effect is to dissolve the anode made of impure copper and thicken the cathode (pure copper) with more pure copper.

## Activity 2: Guided Practice

### Task 17:

Honore works in an REINCHEM industrial chemistry laboratory that produces sodium hydroxide (NaOH), chlorine gas ($Cl_2$), and hydrogen gas ($H_2$) through the electrolysis of sodium chloride (NaCl) solution. The industry uses electrolysis to create these products in large quantities. Honore is tasked with monitoring the electrolysis process in the lab, ensuring the system works efficiently, and understanding how it impacts the production of these useful chemicals. The process involves using a saturated sodium chloride solution in a U-tube setup with carbon rods as electrodes to carry out the electrolysis. The company wants to optimize its operations and improve safety, and Honore needs you to help him to understand the science behind the process.

Referring to the above scenario, perform the following tasks

1. Fill the beaker or glass with 100 ml of distilled water.
2. Add 10g of sodium chloride to 100 ml of distilled water.
3. Warm the mixture and continue adding sodium chloride until a saturated solution is formed.
4. Put the saturated solution in U-tube and fit it with carbon rods and glass syringes.

5. Level the brine solution in the two arms and switch on the circuit.
6. Record any observations made after some time. Identify any gases collected in the syringe

**Debriefing questions**

1. Why is distilled water used initially instead of tap water
2. What does it mean for a salt solution to be "saturated"?
3. What is the role of the carbon rods in the electrolysis setup?
4. What happens when the electrical current is passed through the saturated NaCl solution?
5. What are the products formed during the electrolysis of sodium chloride (NaCl) solution?
6. What gas is produced at the anode during the electrolysis of sodium chloride solution?
7. What gas is produced at the cathode during the electrolysis of sodium chloride solution?
8. Identify the oxidation and reduction half-reactions that occur at the anode and cathode during the electrolysis of sodium chloride solution
9. What happens to the concentration of sodium chloride in the solution as the electrolysis process continues?
10. How does the electrolysis process contribute to the production of sodium hydroxide (NaOH)?

## Activity 3: Application

### Task 18:

The company NEMA works for employs large-scale electrolyzers, which operate on the same principle demonstrated in the laboratory experiment. However, industrial electrolyzers are much more efficient, using high concentrations of alkaline solutions or acidic electrolytes to maximize hydrogen production. By using electrolysis NEMA want you to help her to understand how clean hydrogen is crucial for a sustainable future.

Referring to the above scenario perform the following tasks

1. Fill the beaker or glass with warm water.
2. Take pencils as electrodes with graphite in them to conduct electricity
3. Carefully remove the erasers and metal sleeves so you can sharpen both ends of each pencil,
4. Cut a piece of the cardboard to fit over the beaker, then punch two holes in the center of the cardboard about one inch apart. Push the pencils through the holes and set them in the glass. They should extend into the water, but not touch the bottom of the glass. The cardboard will hold them in place.
5. Connect each pencil to the battery with a crocodile clip lead attached to the exposed graphite (pencil lead). If you do not have crocodile clip leads, use two lengths of wire and strip an inch of insulation off each end. Wrap the wire around the graphite of each pencil and connect the wires to the battery. You may need to use tape to hold the wires in place.

**Debriefing questions**

1. What are the essential components of an electrolytic cell?
2. In this setup, what acts as the anode? What acts as the cathode?
3. What do you expect to observe at the anode during the electrolysis?
4. What do you expect to observe at the cathode during the electrolysis?
5. What is the purpose of the battery in this electrolysis setup?
6. Why is it important to use warm water in this electrolysis experiment?
7. Write the overall chemical equation for the electrolysis of water, including the products formed.

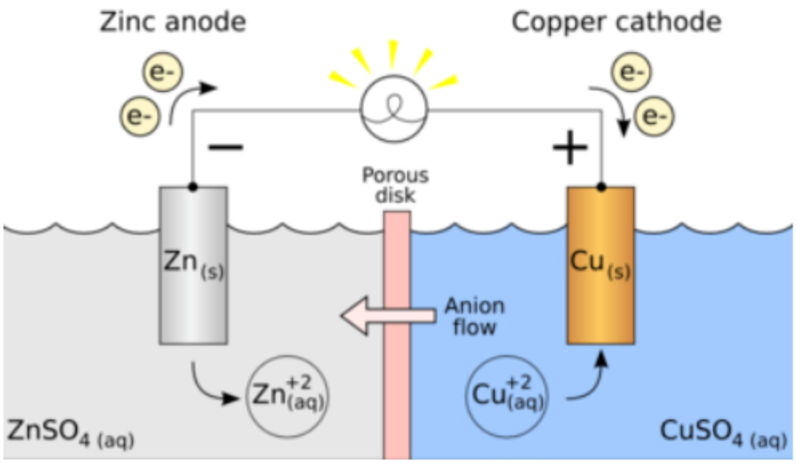
## Topic 3.2: Galvanic cell

### Activity 1: Problem Solving

. **Task 19:**

Access to Internet try to access the video on the following link:

https://www.youtube.com/watch?v=qpFC_Ecu_yQ or observe the picture below which shows how an electrochemical cell works to help you answer the debriefing questions.



Referring to the above video or picture answer the following questions

1. How can you demonstrate the principles of a galvanic cell using household materials?
2. What are the applications of galvanic cells in everyday life?
3. How can you illustrate the concept of oxidation and reduction using a galvanic cell?
4. How does a galvanic cell convert chemical energy into electrical energy?
5. What happens during the oxidation reaction at the anode in a galvanic cell?
6. What is the significance of the electrode potentials of different materials in a galvanic cell?
7. How does the potential difference between the two electrodes create a flow of electrons in a galvanic cell?
8. How do you calculate the standard electrode potential for a galvanic cell?

## Key factor 3.2: Description of galvanic cell

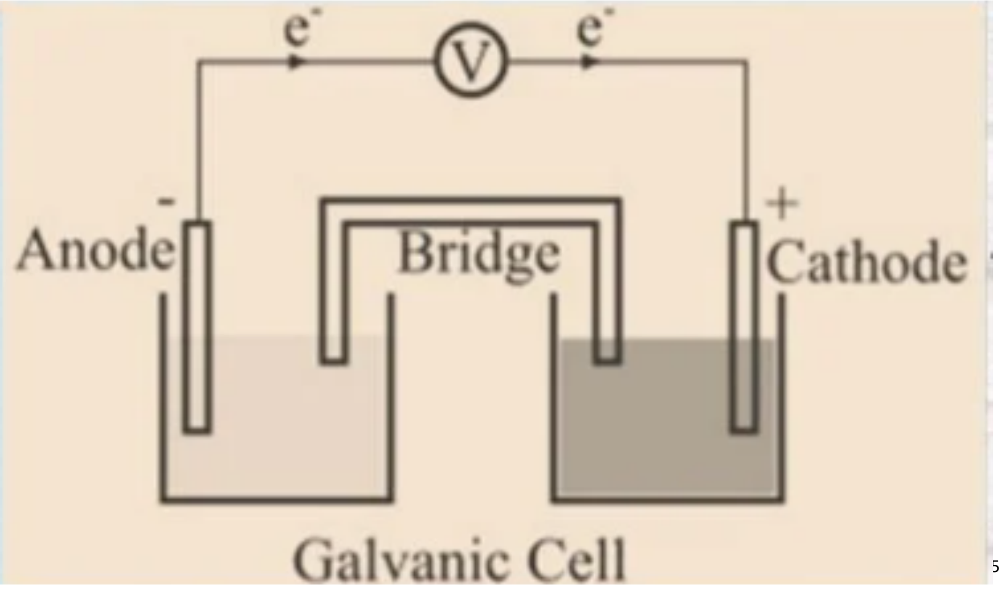
- **Description of galvanic cell**

A galvanic (voltaic) cell is a device used to convert chemical energy of a redox reaction into electrical energy.

✓ **General representation of galvanic cell**

- Spontaneous redox reactions occur in galvanic (voltaic) cells
- Galvanic cell contains electrodes where the oxidation and reduction reactions occur.
- Oxidation occurs at the anode and reduction occurs at the cathode.
- In a galvanic cell, the **anode** is **negatively charged**, since the spontaneous oxidation at the anode is the source of the cell's electrons or negative charge.
- The cathode of a galvanic cell is its positive terminal.
- **Half-cells and Redox reactions in half-cells**

A simple electrochemical cell can be made by connecting together two half-cells with different electrode potentials.



[5]

*Figure 6 Illustration of galvanic cell*

- ○ One half cell releases electron (oxidation at the anode).

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[5] https://scienceinfo.com/difference-and-similarity-galvanic-vs-electrolytic-cell/

- The other half-cell gains electrons (reduction at the cathode).

**Constructing cells from half cells**

- The **oxidation** half-reaction occurs at the anode. In this half-cell, the substance loses electrons.
- Example: **Zinc half-cell** (Zinc metal immersed in a zinc sulfate solution):
- **$Zn\ (s) \xrightarrow{\qquad\qquad} Zn^{2+}\ (aq) + 2e^-$** (Oxidation of zinc)
- The **reduction** half-reaction occurs at the cathode. In this half-cell, the substance gains electrons.
- Example: **Copper half-cell** (Copper ions in copper sulfate solution):
- **$Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$** (Reduction of copper ions)
- Connect the zinc electrode (anode) to the copper electrode (cathode) with a wire. This allows the flow of electrons.
- In the electrochemical cell, the electrons flow from the negative terminal (anode) to the positive terminal (cathode) and the current flows in the opposite direction i.e. from cathode to anode
- Connect the two solutions with a salt bridge (a U-shaped tube filled with a concentrated solution of an inert electrolyte like potassium nitrate ($KNO_3$)).

**The Significance of Salt Bridge**

- The salt bridge is usually an inverted U-tube filled with a concentrated solution of an inert electrolyte. The inert electrolyte is neither involved in any chemical change, nor does it react with the solutions in the two half cells. Generally, salts like KCl, $KNO_3$, $Na_2SO_4$ and $NH_4NO_3$ are used as the electrolytes
- The main function of salt bridge is to prevent the potential difference that arises between the two solutions when they are in contact with each other. This potential difference is called the liquid junction potential.
- It completes the electrical circuit by connecting the electrolytes in the two half cells.
- It prevents the diffusion of solutions from one half-cell to the other.
- It maintains the electrical neutrality of the solutions in the two half cells.

✓ **Types of batteries**

A battery is a device that stores chemical energy and makes it available in an electrical form.

Batteries have many uses including in: Torches, Electrical appliances such as cellphones (long-life alkaline batteries), Digital cameras (lithium batteries), Hearing aids (silver-oxide batteries), Digital watches (mercury/silver-oxide batteries), Military applications (thermal batteries)

- The galvanic cells can be broadly classified into two categories, namely; **primary cells** and **secondary cells.**
- **Primary cells:** is type of cells becomes dead over a period of time and the chemical reaction stops.
    - They cannot be recharged or used again.
    - Some common **examples** are dry cell, mercury cell, etc.
- **Secondary cells:** is type of cells can be recharged by passing direct current through them and can be used again and again.
    - These are the types of batteries found in devices such as smart phones, electronic tablets, and automobiles.
    - Some examples are lead-storage battery, nickel-cadmium storage cell, etc.

✓ **Comparison between galvanic (voltaic) cell and electrolytic cell**

Galvanic (Voltaic) Cell and Electrolytic Cell are two types of electrochemical cells that involve redox reactions. However, they differ significantly in their mechanisms, energy transformations, and applications

- **Difference between electrolytic cell and galvanic cell**

| Feature | Galvanic Cell | Electrolytic Cell |
|---|---|---|
| **Energy Conversion** | Converts chemical energy into electrical energy | Converts electrical energy into chemical energy |
| **Reaction Type** | Spontaneous redox reaction | Non-spontaneous redox reaction |
| **Energy Flow** | Releases electrical energy | Requires external electrical energy input |
| **Cell Potential ($E°cell$)** | Positive | Negative |

| | | |
|---|---|---|
| **Anode** | Negative electrode | Positive electrode |
| **Cathode** | Positive electrode | Negative electrode |
| **Electron Flow** | From anode to cathode through the external circuit | From external source to cathode, then to anode |
| **Examples** | Batteries (like AA, AAA), fuel cells | Electroplating, electrolysis of water, production of aluminum |

**Similarity of electrolytic cell and galvanic**

- ✓ Both types of cells operate based on redox reactions
- ✓ Both typically consist of two electrodes (anode and cathode) immersed in an electrolyte solution.
- ✓ In both cells the oxidation reaction occurs at anode while the reduction occurs at cathode.
- ✓ Both types of cells involve the use of direct current (DC) in some capacity
- ✓ In both cells, energy conversion takes place

## Activity 2: Guided Practice

### Task 20:

RUKUNDO works in Prudacell industry which manufacture alkaline batteries that use zinc and manganese dioxide ($MnO_2$) to produce electrical energy. RUKUNDO want you to help him to understand how the zinc-copper galvanic cell is used as a teaching tool to illustrate how chemical reactions can produce electrical energy.

Referring to the above perform the following tasks

1. Prepare two separate beakers: one containing zinc sulfate ($ZnSO_4$) solution and the other containing copper sulfate ($CuSO_4$) solution.
2. Place a zinc strip in the zinc sulfate solution and a copper strip in the copper sulfate solution.

3. Connect the zinc strip to the negative terminal of the voltmeter using an alligator clip or wire.
4. Connect the copper strip to the positive terminal of the voltmeter.
5. Place a U-shaped tube filled with a concentrated solution of potassium nitrate ($KNO_3$) or sodium chloride (NaCl) to connect the two half-cells and allow the cell to function.
6. Observe and record the voltage generated by the galvanic cell.

**Debriefing questions**

1. What role do the zinc and copper strips play in the galvanic cell?
2. What is the purpose of the U-shaped tube filled with $KNO_3$ or NaCl?
3. What is the expected voltage output of the zinc-copper galvanic cell?
4. What happens to the zinc strip during the reaction, and why?
5. What happens to the copper strip during the reaction, and why?
6. How can you identify the anode and cathode in the galvanic cell?
7. Identify the Half-Reactions

## Activity 3: Application

### Task 21:

Mugisha is preparing for a camping trip and plan to use a flashlight powered by a dry cell battery. For better preparetion he want to understanding how the dry cell works and the limitations associated with. However he is asking you to explain to him how does the chemical energy in the dry cell get converted into electrical energy that will help him make informed decisions about his flashlight usage during the trip

Referring to the above scenario, perform the following tasks and answer the debriefing questions

1. Carefully dissemble an old, used dry cell battery (with appropriate safety precautions).

2. Observe the internal components and try to identify the different materials used.
3. Measure the voltage of a new dry cell battery using a multimeter. Record the initial voltage.
4. Connect the battery to a small bulb or a simple circuit with a known resistance
5. Measure the current flowing through the circuit using a multimeter.
6. Measure the time it takes for the battery voltage to drop significantly or for the device to stop functioning.

**Debriefing questions**

1. What components did you observe inside the dry cell, and how do you think the dry cell battery related to galvanic cell?
2. How did the battery's performance change over time
3. Can Mugisha recharge a dry cell battery?
4. Are there any alternative power sources for my flashlight that might be more suitable for camping?
5. Discuss the specific chemical reactions happening inside the dry cell battery?
6. Based on the principles of a galvanic cell classify the dry cell as primary or secondary cell

## Topic 3.3: Electromotive force of the cell

### Activity 1: Problem Solving

#### Task 22:

A team in SIBOTECH Company is studying the degradation of batteries over time. A team of scientist in the company need to analyze how factors such as temperature, concentration of ions, and presence of impurities affect the EMF of a battery using the principles of electrochemistry.

Referring to the scenario above, do the following tasks

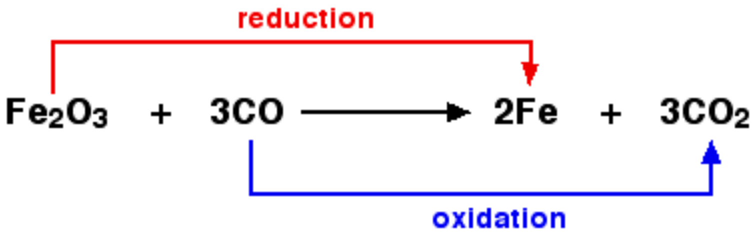
1. Explain the electromotive force (EMF)?
2. How is EMF related to cell potential?
3. What are the units for measuring EMF?

4. How does the gradual decrease in electrolyte concentration affect the EMF of a battery over time?
5. What is the relationship between the standard electrode potential and the EMF of a cell?
6. What is the relationship between the standard electrode potential and the EMF of a cell?
7. How can you calculate the overall EMF of an electrochemical cell?
8. How do the half-reactions of oxidation and reduction contribute to the EMF of a cell?

## Key Facts 3.3 Determination of electromotive force of the cell

### Electrochemical cell reactions

- **Oxidation and reduction reaction:** also called redox reaction, any chemical reaction in which the oxidation number of a participating chemical species changes.
  - Most oxidation-reduction (redox) processes involve the transfer of oxygen atoms, hydrogen atoms, or electrons,
  - **Oxidation** is the loss of electrons or an increase in the oxidation state of an atom, an ion, or of certain atoms in a molecule or gain oxygen
  - **Reduction** is the gain of electrons or a decrease in the oxidation state of an atom, an ion, or of certain atoms in a molecule (a reduction in oxidation state) or loss of oxygen.



$$Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$$

- **General Rules for Assigning Oxidation States**
  - The oxidation state of an element in its pure form (e.g., $O_2$, $N_2$, Fe) is always 0.

- The oxidation state of a monatomic ion is equal to its charge.
- Oxygen generally has an oxidation state of -2 in most compounds, except in peroxides where it is -1 and in compounds with fluorine where it can be positive.
- Hydrogen generally has an oxidation state of +1 when bonded with non-metals, and -1 when bonded with metals.
- Fluorine always has an oxidation state of -1 in compounds.
- The sum of the oxidation states of all atoms in a neutral compound is 0.
- The sum of the oxidation states of all atoms in a polyatomic ion equals the charge of the ion.
- Alkali metals (Li, Na, K, etc.) have an oxidation state of +1 in their compounds.
- Alkaline earth metals (Be, Mg, Ca, etc.) have an oxidation state of +2 in their compounds.

  **Worked example:** Consider the reaction between zinc and copper ions

  $\mathbf{Zn_{(s)} + Cu^{2+}_{(aq)} \longrightarrow Zn^{2+}_{(aq)} + Cu_{(s)}}$

- **Let calculate the oxidation states of the elements involved in the reaction.**

  **Zn** in its elementary form has an oxidation state of **0**.

  **$Cu^{2+}$** has an oxidation state of **+2**.

  **$Zn^{2+}$** has an oxidation state of **+2**.

  **Cu** in its elemental form has an oxidation state of **0**.

- **Identify Changes in Oxidation States**

  Zinc (Zn): Changes from 0 to +2 **(oxidation).**

  Copper (Cu): Changes from +2 to 0 **(reduction).**

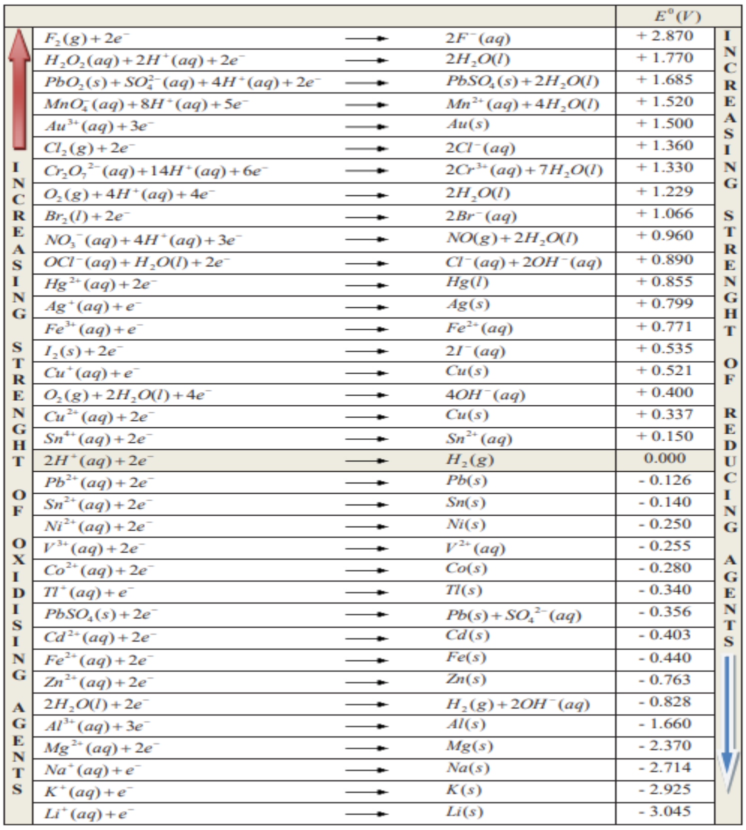
- **Write the Half-Reactions**

  Oxidation Half-Reaction: $\mathbf{Zn_{(s)} \longrightarrow Zn^{2+}_{(aq)} + 2e^-}$

  Reduction Half-Reaction: $\mathbf{Cu^{2+}_{(aq)} + 2e^- \longrightarrow Cu_{(s)}}$

**Standard Electrode Potential (SEP)**

- In electrochemistry, standard electrode potential is a measure of the reducing power of any element or compound.
- When a metal electrode is dipped in a solution containing its metal ions, a potential difference is developed at the metal /solution interface. This potential difference is called the electrode potential.
- **For example**, when a copper rod is dipped in a solution containing $Cu^{2+}$ ions, the $Cu^{2+}$ ions gain electrons from the copper rod leaving positive charge on the copper rod. As a result, a potential difference is set up between the copper rod and the solution and is called the electrode potential of copper.
- The electrode chosen as having the value of “zero” is called the Standard Hydrogen
- Electrode (SHE). The SHE consists of 1 atm of hydrogen gas bubbled through a 1 M strong acid solution, usually at room temperature.
- Other standard electrode potentials can be determined using the SHE



| | | | $E^{\circ}(V)$ |
|---|---|---|---|
| $F_2(g)+2e^-$ | $\longrightarrow$ | $2F^-(aq)$ | +2.870 |
| $H_2O_2(aq)+2H^+(aq)+2e^-$ | $\longrightarrow$ | $2H_2O(l)$ | +1.770 |
| $PbO_2(s)+SO_4^{2-}(aq)+4H^+(aq)+2e^-$ | $\longrightarrow$ | $PbSO_4(s)+2H_2O(l)$ | +1.685 |
| $MnO_4^-(aq)+8H^+(aq)+5e^-$ | $\longrightarrow$ | $Mn^{2+}(aq)+4H_2O(l)$ | +1.520 |
| $Au^{3+}(aq)+3e^-$ | $\longrightarrow$ | $Au(s)$ | +1.500 |
| $Cl_2(g)+2e^-$ | $\longrightarrow$ | $2Cl^-(aq)$ | +1.360 |
| $Cr_2O_7^{2-}(aq)+14H^+(aq)+6e^-$ | $\longrightarrow$ | $2Cr^{3+}(aq)+7H_2O(l)$ | +1.330 |
| $O_2(g)+4H^+(aq)+4e^-$ | $\longrightarrow$ | $2H_2O(l)$ | +1.229 |
| $Br_2(l)+2e^-$ | $\longrightarrow$ | $2Br^-(aq)$ | +1.066 |
| $NO_3^-(aq)+4H^+(aq)+3e^-$ | $\longrightarrow$ | $NO(g)+2H_2O(l)$ | +0.960 |
| $OCl^-(aq)+H_2O(l)+2e^-$ | $\longrightarrow$ | $Cl^-(aq)+2OH^-(aq)$ | +0.890 |
| $Hg^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Hg(l)$ | +0.855 |
| $Ag^+(aq)+e^-$ | $\longrightarrow$ | $Ag(s)$ | +0.799 |
| $Fe^{3+}(aq)+e^-$ | $\longrightarrow$ | $Fe^{2+}(aq)$ | +0.771 |
| $I_2(s)+2e^-$ | $\longrightarrow$ | $2I^-(aq)$ | +0.535 |
| $Cu^+(aq)+e^-$ | $\longrightarrow$ | $Cu(s)$ | +0.521 |
| $O_2(g)+2H_2O(l)+4e^-$ | $\longrightarrow$ | $4OH^-(aq)$ | +0.400 |
| $Cu^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Cu(s)$ | +0.337 |
| $Sn^{4+}(aq)+2e^-$ | $\longrightarrow$ | $Sn^{2+}(aq)$ | +0.150 |
| $2H^+(aq)+2e^-$ | $\longrightarrow$ | $H_2(g)$ | 0.000 |
| $Pb^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Pb(s)$ | -0.126 |
| $Sn^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Sn(s)$ | -0.140 |
| $Ni^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Ni(s)$ | -0.250 |
| $V^{3+}(aq)+2e^-$ | $\longrightarrow$ | $V^{2+}(aq)$ | -0.255 |
| $Co^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Co(s)$ | -0.280 |
| $Tl^+(aq)+e^-$ | $\longrightarrow$ | $Tl(s)$ | -0.340 |
| $PbSO_4(s)+2e^-$ | $\longrightarrow$ | $Pb(s)+SO_4^{2-}(aq)$ | -0.356 |
| $Cd^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Cd(s)$ | -0.403 |
| $Fe^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Fe(s)$ | -0.440 |
| $Zn^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Zn(s)$ | -0.763 |
| $2H_2O(l)+2e^-$ | $\longrightarrow$ | $H_2(g)+2OH^-(aq)$ | -0.828 |
| $Al^{3+}(aq)+3e^-$ | $\longrightarrow$ | $Al(s)$ | -1.660 |
| $Mg^{2+}(aq)+2e^-$ | $\longrightarrow$ | $Mg(s)$ | -2.370 |
| $Na^+(aq)+e^-$ | $\longrightarrow$ | $Na(s)$ | -2.714 |
| $K^+(aq)+e^-$ | $\longrightarrow$ | $K(s)$ | -2.925 |
| $Li^+(aq)+e^-$ | $\longrightarrow$ | $Li(s)$ | -3.045 |

*Figure 7 Standard electrode potential of common reduction reactions*

- **Table of Standard Electrode Potential (SEP)**

[6]

**Electrode potential/electromotive force ($E^0$)**

Electromotive force (EMF) is the total voltage developed by an electrochemical cell when no current is flowing (open circuit condition).

- **Electromotive force (EMF) of a cell and cell notation**
  - Cell notation (also known as **cell diagram**) is a shorthand way of representing an electrochemical cell, indicating the order of the half-reactions, the electrodes, and the direction of electron flow.
  - **The general format for cell notation is**:

Anode (oxidation) |Anode Solution (concentration)|| Cathode Solution (concentration) |Cathode (reduction)

**Example:** Consider the reaction between zinc and copper ions

$$Zn_{(s)} + Cu^{2+}_{(aq)} \longrightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$$

For the zinc-copper cell, the cell notation is: $Zn_{(s)} | Zn^{2+}_{(aq)} || Cu^{2+} | Cu_{(s)}$

- **Anodic and cathodic potential**
  - The anodic potential is the potential difference between an anode and the electrolyte solution
  - The cathodic potential is the potential difference between a cathode and the electrolyte solution.
- **Overall potential of the cell**
  - The overall potential of the cell, also known as the electromotive force (EMF), is the maximum potential difference between the two electrodes of a cell when no current is flowing.
- **Emf calculation**

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[6] www.chemeddl.org/services/moodle/media/QBank/GenChem/Tables/EStandardTable.htm)

- Write the oxidation and reduction half-reactions for the cell.
- Look up the reduction potential, $E^0$ reduction, for the reduction half-reaction in a table of reduction potentials.
- Look up the reduction potential for the reverse of the oxidation half-reaction and reverse the sign to obtain the oxidation potential.
- For the oxidation half-reaction, **$E^0_{oxidation} = —E^0_{reduction}$.**
- Add the potentials of the half-cells to get the overall standard cell potential.
- **$E^0_{cell} = E^0_{reduction} + E^0_{oxidation}$**
- **Example:** Find the standard cell potential for an electrochemical cell with the following cell reaction.
- $Zn_{(s)} + Cu^{2+}_{(aq)} \longrightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$

1) **Write the half-reactions for each process.**

$Zn_{(s)} \longrightarrow Zn^{2+}_{(aq)} + 2e^-$

$Cu^{2+}_{(aq)} + 2\ e^- \longrightarrow Cu_{(s)}$

2) Look up the standard potentials for the reduction half-reaction.

   **$E^o$ reduction of $Cu^{2+}$** = + 0.339 V

3) Look up the standard reduction potential for the reverse of the oxidation reaction and change the sign.

   **$E^o_{reduction}$ of $Zn^{2+}$** = - 0.762 V

   **$E^o_{oxidation}$ of Zn** = — (—0.762 V) = **+** 0.762 V

4) **Add the cell potentials together to get the overall standard cell potential.**

   **Oxidation reaction** $Zn_{(s)} \longrightarrow Zn^{2+}_{(aq)} + 2e^-$ $E^0 = + 0.762$ V

   **Reduction reaction** $Cu^{2+}_{(aq)} + 2\ e^- \longrightarrow Cu_{(s)}$ $E^0= + 0.339$ V

5) Look up the standard reduction potential for the reverse of the oxidation reaction and change the sign.

   - **How do we know which metal will become oxidized and which metal ion reduced?**
     - By looking at a table of standard reduction potentials! One of the half-reactions must be reversed to yield an oxidation.
     - Reverse the half-reaction that will yield the highest (positive) net emf for the cell.

- Remember that when one reverses a reaction, the sign of $E^0$ (+ or –) for that reaction is also reversed.
- **For example: Consider the following table of standard reduction potentials**

| **In aqueous solution at $25^0C$** | |
|---|---|
| $Hg^{2+}_{(aq)} + 2e^- \longrightarrow Hg_{(l)}$ | $E^0$= +0.86 V |
| $I_{2(S)} + 2e^- \longrightarrow 2I^-_{(aq)}$ | $E^0$= -0.54V |
| $2H^+_{(aq)} + 2e^- \longrightarrow H_{2(g)}$ | $E^0$= +0.00 V |
| $Zr^{4+}_{(aq)} + 4e^- \longrightarrow Zr_{(s)}$ | $E^0$= -1.53 V |
| $Rb^+_{(aq)} + e^- \longrightarrow Rb_{(s)}$ | $E^0$= -2.93 V |

- The potential generated by a cell constructed from standard Zr and $I_2$ electrodes may be calculated. From the table, we write a balanced reduction half-reaction for each electrode and copy down the reduction potentials.

$\mathbf{I_{2(S)} + 2e^- \longrightarrow 2I^-_{(aq)}}$ $E^0$= -0.54V

$\mathbf{Zr^{4+}_{(aq)} + 4e^- \longrightarrow Zr_{(s)}}$ $E^0$= -1.53 V

Reversing which reaction will yield most positive standard reduction potential? Let us try both.

**Case 1 reverse the iodine reduction:** $E^0$=-(0.54V)=-0.54V

**Case 1 reverse the Zirconium reduction:** $E^0$= -(-1.53 V) = + 1.53 V

Thus, the highest positive potential is found by using the Zr oxidation half-reaction because:

**+ 1.53 V > – 0.54 V**

Thus, the standard cell potential will be $\mathbf{E^o_{ox}}$ **(Zr) +** $\mathbf{E^o_{red}}$ **($I_2$)**

$\mathbf{E^o_{Cell}}$ **= (+0.54V) + (+1.53V) = +2.07V**

Even though we had to multiply the iodine reduction by a factor of 2 so that the electrons consumed would balance with those produced by the zirconium oxidation, we do NOT multiply the iodine reduction potential by this factor. In manipulating potentials, we should only change the signs of the values, not the magnitude.

- **A negative** reduction potential tells us that the zirconium ion is harder to reduce (is a worse oxidizing agent) than is the hydrogen ion; this also tells us that zirconium metal is a better reducing agent than is hydrogen gas.

- **A positive** reduction potential tells us that the iodide ion is easier to reduce (is a better oxidizing agent) than is the hydrogen ion; this also tells us that iodine is a worse reducing agent than is hydrogen gas.
- In general, the electrode with the more positive value of electrode potential is the cathode (the one which undergoes reduction) and the electrode with more negative value of electrode potential is the anode (easily oxidised).

**Prediction of spontaneity of redox reactions**

- $E^0$ will be positive for the case where the reaction is spontaneous
- $E^0$ will be zero for a redox reaction at equilibrium
- $E^0$ will be negative for the case where the reaction is not spontaneous, i.e., the reverse direction reaction is spontaneous

## Activity 2: Guided Practice

### Task 23:

We have the following reactions

$Mg^{2+}_{(aq)} + 2e \longrightarrow Mg_{(S)}$ $E^0 = -2.37V$

$Fe^{2+}_{(aq)} + 2e \longrightarrow Fe_{(S)}$ $E^0 = -0.44V$

Referring to the above reactions do the following:

1. Write the half equation that take a place at anode electrode
2. Write the half equation that take a place at anode electrode
3. Calculate the electromotive force of the cell
4. Draw the cell notation.
5. Justify if the cell will produce energy.

## Activity 3: Application

### Task 24:

The table below shows some values for standard electrode potentials.

| Electrode | Electrode reactions | $E^0/V$ |
|---|---|---|
| A | $Mn^{2+}_{(aq)} + 2e^- \rightleftharpoons Mn_{(s)}$ | -1.18 |
| B | $Zn^{2+}_{(aq)} + 2e^- \rightleftharpoons Zn_{(s)}$ | -0.762 |
| C | $Cu^{2+}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$ | +0.339 |
| D | $2H^+_{(g)} + 2e^- \rightleftharpoons H_{2(g)}$ | ? |
| E | $Fe^{2+}_{(aq)} + 2e^- \rightleftharpoons Fe_{(s)}$ | -0.44 |

Referring to the above table, do the following:

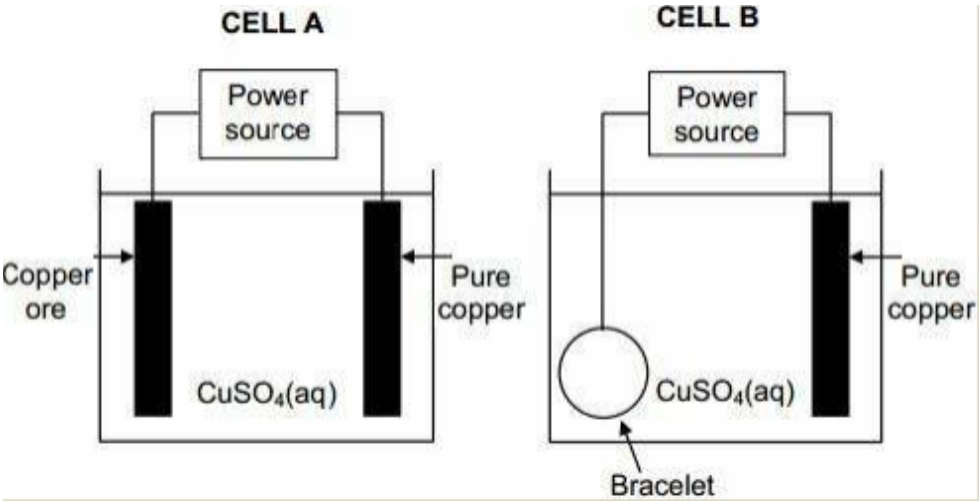
1. Give the name of electrode **D** and indicate its role in the determination of standard electrode potentials.
2. What is the value of the standard electrode potential for electrode **D**?
3. The electrochemical cell set up between electrodes **B** and **C** can be represented by the cell diagram:

$$Zn_{(s)} \mid Zn^{2+}_{(aq)} \parallel Cu^{2+}_{(aq)} \mid Cu_{(s)}$$

   a. Calculate the e.m.f. of this cell.
   b. State, which would be the positive electrode.
   c. Write an equation to show the overall reaction in the cell
   d. Justify if the cell will produce energy

## Formative Assessment

1. Which of the following substances is an electrolyte?
    a) Mercury
    b) Copper
    c) Sodium sulphate
    d) Aluminium
2. Which of the following substances is a weak electrolyte?
    a) Dilute hydrochloric acid
    b) Dilute sulphuric acid
    c) A solution of potassium bromide.
    d) Carbonic acid
3. Some cells, such as the nickel-cadmium cell used in calculators and electric shavers, can be recharged. Others, such as those used in watches and torches, cannot be recharged. Are rechargeable cells primary or secondary cells?
4. Which of these is a TRUE statement about galvanic cells?
    a) Galvanic cells convert chemical energy to electrical energy using an oxidation-reduction reaction.
    b) Galvanic cells convert electrical energy to chemical energy using an oxidation-reduction reaction.
    c) Galvanic cells convert chemical energy to electrical energy using a decomposition reaction.
    d) Galvanic cells convert electrical energy to chemical energy using electrolysis.
5. State two differences and two similarities between an electrochemical cell and an electrolytic cell.
6. What is the difference between electrolytic extraction of a metal and electroplating?
7. What is the material for cathode and anode during electro refining of impure copper? Potential contamination of nearby evaluating the environmental impact of the chemicals.
8. The simplified diagrams below represent two electrochemical cells, A and B, used in industry. Cell A is used in the purification of copper ore containing silver and platinum impurities. Cell B is used to electroplate a bracelet with a layer of copper.



a) Write down the name of the type of electrochemical cell of which the above two cells are examples.

b) Pure copper is used as one of the electrodes in each of the cells above. In which cell (A or B) is the pure copper the:

i) Cathode

ii) Anode

9. Define standard electrode potential.

10. Is it possible to use another standard electrode than SHE? Justify your answer.

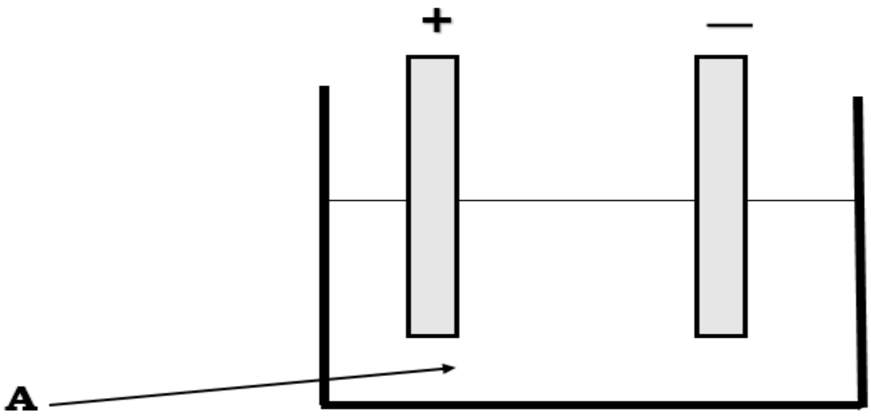
11. Answer by **True** or **False**.

a) Hydrogen electrode which is the reference electrode can be used as Anode or Cathode.

b) If hydrogen electrode acts as cathode, hydrogen is oxidised.

c) With the aid of a diagram, explain how the standard electrode potential of zinc is measured.

12. The chemical **A** is sodium chloride



a) What do you understand by electrolytic cell

b) Write the formula of **A**

c) When electricity is passed through **A**, what is produced at

  i) The anode?

  ii) The Cathode?

d) Write the half equation showing the reaction at

  i) The anode.

  ii) The cathode.

e) At cathode there is……………………… (**Reduction, Oxidation**)

f) At anode there is……………………… **(Reduction, Oxidation)**

13. The table below shows some values for standard electrode potentials.

| Electrode | Electrode reactions | $E^0/V$ |
|---|---|---|
| A | $Mn^{2+}_{(aq)} + 2e^- \rightleftharpoons Mn_{(s)}$ | -1.18 |
| B | $Zn^{2+}_{(aq)} + 2e^- \rightleftharpoons Zn_{(s)}$ | -0.762 |
| C | $Cu^{2+}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$ | +0.339 |
| D | $2H^+_{(g)} + 2e^- \rightleftharpoons H_{2(g)}$ | ? |
| E | $Fe^{2+}_{(aq)} + 2e^- \rightleftharpoons Fe_{(s)}$ | -0.44 |

a) Give the name of electrode **D** and indicate its role in the determination of standard electrode potentials.

b) What is the value of the standard electrode potential for electrode **D**?

c) The electrochemical cell set up between electrodes **B** and **C** can be represented by the cell diagram:

$$Zn_{(s)} \mid Zn^{2+}_{(aq)} \parallel Cu^{2+}_{(aq)} \mid Cu_{(s)}$$

d) Calculate the e.m.f. of this cell.

e) State, which would be the positive electrode.

f) Write an equation to show the overall reaction in the cell

g) Justify if the cell will produce energy

14. Calculate the mass of silver deposited at the cathode when a current of 1.5 A is passed for 10 minutes in a silver nitrate solution.
15. Suppose you electrolyze a solution of nickel (II) sulfate (NiSO4) and a solution of zinc sulfate ($ZnSO_4$) with the same quantity of electric charge, and if 15 grams of nickel are deposited from the nickel sulfate solution, how much zinc will be deposited from the zinc sulfate solution?

## Points to Remember

- ✓ Electrolysis is a process of decomposing, ionic compounds into their elements by passing a direct electric current through the compound in a fluid form.
- ✓ Component of electrolytic cell are electrode and electrolyte.
- ✓ Cathode are negative while anode are positive electrodes
- ✓ Electrolysis found use in production of many chemicals, electroplating, metal extraction and purification
- ✓ Spontaneous reactions occur in galvanic (voltaic) cells; non-spontaneous reactions occur in electrolytic cells
- ✓ There are two types of electrochemical cells: galvanic (voltaic) cells and electrolytic cells.
- ✓ A galvanic (voltaic) cell is a device used to convert chemical energy of a redox reaction into electrical energy
- ✓ Electrolytic cell dissociates ionic compound into cation and anion when electric current is supplied through it.

## Self-Reflection

1. Fill in and complete the self-assessment table below to assess your level of knowledge, skills and attitudes after covering this unit.
2. There are no right or wrong ways to answer this assessment. It is for your own reference and self-reflection on the knowledge, skills and attitudes acquisition during the learning process.
3. Think about yourself:
   a) Do you think that you have knowledge, skills or attitudes to do the tasks?
   b) How well?
4. Read the statements across the top. Put a check in a column that best represents your level of knowledge, skills and attitudes.

| **My experience**<br>**Knowledge, skills and attitudes** | **I do not have any experience doing this.** | **I know a little about this.** | **I have some experience doing this.** | **I have a lot of experience with this.** | **I am confident in my ability to do this.** |
|---|---|---|---|---|---|
| Explain the basic concepts of electrochemistry, such as oxidation, reduction, and redox reactions. | | | | | |
| Describe the process of electrolysis | | | | | |
| Explain the Faraday's first and second laws of electrolysis | | | | | |

| My experience<br>Knowledge, skills and attitudes | I do not have any experience doing this. | I know a little about this. | I have some experience doing this. | I have a lot of experience with this. | I am confident in my ability to do this. |
|---|---|---|---|---|---|
| Identify the structure and function of galvanic (voltaic) cells | | | | | |
| Differentiate between galvanic (voltaic) and electrolytic cell | | | | | |
| Recognize the types of redox reactions | | | | | |
| Explain the concept of standard electrode potential | | | | | |
| Describe how to calculate and interpret the overall EMF of a cell | | | | | |
| Interpret the diagram of an electrochemical cell | | | | | |
| Differentiate primary and secondary cells | | | | | |
| Recognize the industrial applications of electrolysis, | | | | | |

5. Fill in the table above and share results with the trainer for further guidance.

| Areas of strength | Areas for improvement | Actions to be taken to improve |
|---|---|---|
| **1.** | **1.** | **1.** |
| **2.** | **2.** | **2.** |
| **3.** | **3.** | **3.** |

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