The Patent Officer

An introduction to energy and thermodynamics

This is an interdisciplinary problem that explores energy and thermodynamics in the fields of physics and chemistry

Intended Learning Outcomes

(For more detailed learning outcomes see inside document)

- **Patent 1:** Fluids
- **Patent 2:** Work-Energy Theorem; conservation of energy; conservation of momentum
- **Patent 3:** Kinetic-, gravitational- and potential energy; free-body force diagrams; simple harmonic motion (SHM); thermal properties of common materials
- **Patent 4:** Thermodynamics; Ideal Gas Law; Kinetic Theory of Gases; latent and specific heat; Cycles and efficiencies; irreversibility, disorder and entropy
- **Patent 5:** Maxwell-Boltzmann distribution
- **Patent 6:** Free energy; enthalpy and entropy; calorimeters; equilibrium constants
- **Patent 7:** REDOX processes; galvanic and electrolytic cells; electrochemical processes; wave-particle duality of light

KEYWORDS:

Archimede's principle, buoyancy, Boyle's law, calorimeters, collisions, conservation of energy, conservation of linear momentum, conservative/non-conservative forces, cycles and efficiencies, density, disorder, *electrochemical processes*, enthalpy, entropy, *equilibrium constants (of chemical processes)*, equipartition theorem, first law of thermodynamics, fluids, free-body force diagrams, free energy, *galvanic and electrolytic cells*, gravitational potential energy, *half reactions*, heat capacity, heat engines, Ideal Gas Law, irreversibility, kinetic energy, kinetic theory of gases, latent heat, linear expansion, linear momentum, Maxwell-Boltzmann distribution, mean free path, Pascal's Principle, potential energy, pressure, PV diagrams, *REDOX processes*, refrigerators, second law of thermodynamics, simple harmonic motion (SHM), specific heat, spontaneous processes, temperature, thermal equilibrium, thermal properties, thermodynamics, volume expansion, wave-particle duality, work-energy theorem, zeroth law of thermodynamics

Contents

The original form of the problem is a four week (15 credit) module in the IScience programme at the University of Leicester providing part of an introduction to energy and thermodynamics in Physics and Chemistry. The problems are posed as a set of patent applications that may be used as a whole or individually. With the exception of the Feynman Ratchet, the names given to the devices are fictitious.

Intended Learning Outcomes (in detail)

By the end of this problem students should be able to:

Patent 1

- Define Pascal's Principle for fluids and to recall the equations used to calculate the pressure and density of a) a liquid under compression and b) a free standing liquid.
- Explain buoyancy; state Archimedes's Principle and apply it to simple physical models.

Patent 2

- Describe and used the Work-Energy Theorem and the Law of Conservation of Energy to solve simple physical models.
- Describe the difference between conservative and non-conservative forces.
- Apply the principle of Conservation of Momentum in simple two or three body collisions.

Patent 3

- Define kinetic energy and gravitational and potential energy. Be able to draw simple free-body force diagrams in order to solve problems.
- Define the concept of Simple Harmonic Motion and recall the equations that define this motion. Derive the motion of a simple pendulum from Newton's Second law. Recognise situations where the idealised equations can be applied in order to model real life situations (simple pendulum) and solve such situations.
- Understand the thermal properties of common materials and be able to apply the equations of linear and volume expansion.

Patent 4

- Define and apply the Zeroth law of Thermodynamics. Understand the concepts of thermal equilibrium and temperature.
- Define and apply Boyle's Law and the Ideal Gas Law.
- Describe the Kinetic Theory of Gases, including the Equipartition Theorem and the concept of Mean Free Path.
- Recall and use the equations for Heat capacity, Specific Heat and Latent Heat.
- Define and apply the First Law of Thermodynamics. Be able to draw PV diagrams of different thermodynamic processes; be able to calculate the work done from a PV diagram. Understand the importance of quasi-static processes.

- Define and apply the Second Law of Thermodynamics. Understand heat engines and refrigerators within the context of the Second Law of Thermodynamics.
- Describe Cycles and Efficiencies and be able to carry out simple calculations.
- Describe the physical concepts of irreversibility, disorder and entropy.

Patent 5

- Recall the mathematical form of the Maxwell-Boltzmann speed distribution function, understand its physical origin and be able to state the most probably speed, , for a given temperature.

Patent 6

- Define the concepts of free energy, enthalpy and entropy and be able to apply them in the context of the laws of thermodynamics to predict the spontaneity of a chemical process.
- Explain the workings of both constant volume and pressure calorimeters and to measure the enthalpy or internal energy change by using calorimetric data.
- Determine equilibrium constants for chemical processes and use these values to derive the free energy change (hence predict the position of the equilibrium) of a given process.

Patent 7

- Define oxidation, reduction and oxidation states and be able to explain a redox process in these terms.
- Describe the workings of galvanic and electrolytic cells both in terms of the equipment used and on the particle level (i.e. taking the spontaneity of the chemical processes occurring into account).
- Be able to predict the spontaneity of an electrochemical process by identifying the half-reactions occurring in a redox process and applying the appropriate physical data (i.e. the half-cell potentials).
- Recall the wave-particle duality of light and calculate the energy of a photon of light from its frequency (or wavelength) and vice versa.

Reading List

The reading list is that provided for the original module. Other equivalent textbooks are available.

Ready to Study

- Breithhaupt, J., ***Physics***. Palgrave Foundations.
- Lewis, R. & Evans, W., ***Chemistry***. Palgrave Foundations.
- Trefil, J. & Hazen, R. M., ***Sciences: An Integrated Approach***. Wiley.
- Knight, R.D., Jones, B. & Field, S. ***College Physics: A Strategic Approach.*** Pearson.

Essential

- Burrows, A., Holman, J., Parsons, A., Pilling, G. & Price, G., ***Chemistry^3.*** Oxford University Press.
- Atkins, P.W. & de Paula, J. ***Atkins' Physical Chemistry***. Oxford University Press.
- Tipler, P.A. & Mosca, G., ***Physics for Scientists and Engineers***. Freeman.

Further

- Zumdahl, S. ***Chemical Principles***. Houghton Mifflin.
- Brown, T.L., LeMay, H.E. & Bursten, B.E. ***Chemistry: The Central Science.*** Prentice Hall.
- Harris, D.A. ***Bioenergetics at a glance***. Blackwell
- Mattsson, E. ***Basic corrosion technology for scientists and engineers.*** Maney Publishing *in association with* The Institute of Materials, Minerals and Mining
- McMurray, J. & Fay, R.C. ***Chemistry.*** Pearson

Problem Statements

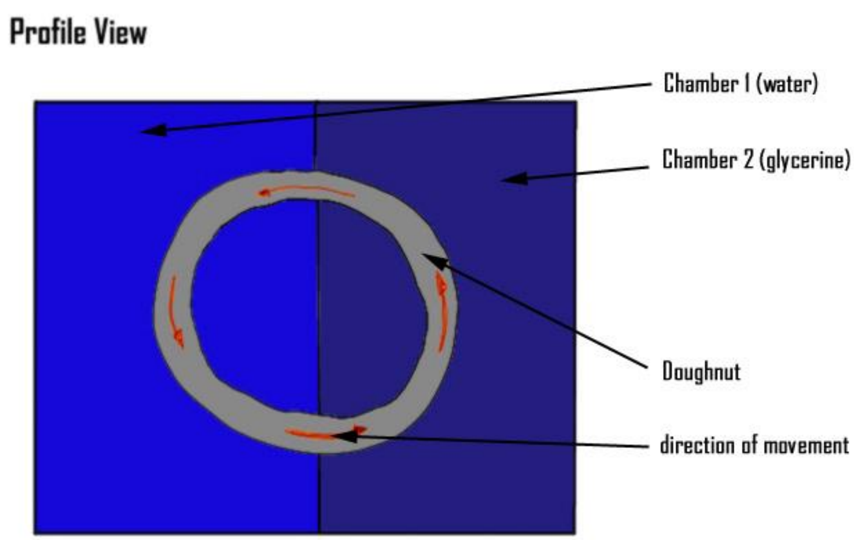
Patent #01-2011: The Aegle Turbine

Inventor: Ms Fiona Aegle
27 Broom Street, Crewe, Cheshire, CW1 3RF

Abstract:

The invention exploits Archimedes's Principle to create a machine that can run indefinitely without input of energy.

Description:



The turbine consists of a solid 'doughnut' of material, which is free to rotate about its central point. The doughnut is contained within two chambers of liquid, which are sealed from one another (and the doughnut prevents any leakage between the two). Chamber 1 contains water, Chamber 2 contains glycerine.

Any liquid exerts a buoyancy on a solid object within it, which is related to its density. As glycerine is denser than water, the side of the doughnut suspended in chamber 2 will experience a greater upward force than the side in chamber 1, and the doughnut will rotate, *ad infinitum*.

Claim:

I have not constructed a functioning prototype and I have not yet given thought to a mechanism for extracting the energy and putting it to work, but I am confident the idea can be put into practice.

Patent #02-2011: Magnetic Accelerator

Inventor: Mr Thomas Vister
22 Dunvegan Road, Kingston-Upon-Hull, HU8 9PD

Abstract:

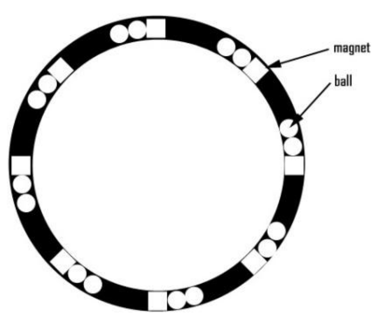
This device consists of a series of balls on a circular track, which once set in motion will continue to move forever.

Description:

The device operates on the same principle as the popular Newton's Cradle – where momentum is imparted from one ball to another (momentum is always conserved).

The balls sit in pairs on a circular track, and the first is released from rest. It is magnetically attracted towards the first pair. When it hits the second ball, its momentum is transferred to the third ball, which continues on with the same speed the first impacted with.

This ball then meets the next pair, where the same thing occurs. This continues around and around the track.



Claim:

Once the first ball has been released, the system will continue to move without interruption.

Patent #03-2011: A Pendulum Thermometer

Inventor: J Arthur Crank
22 Progress Way, London N22

Abstract:

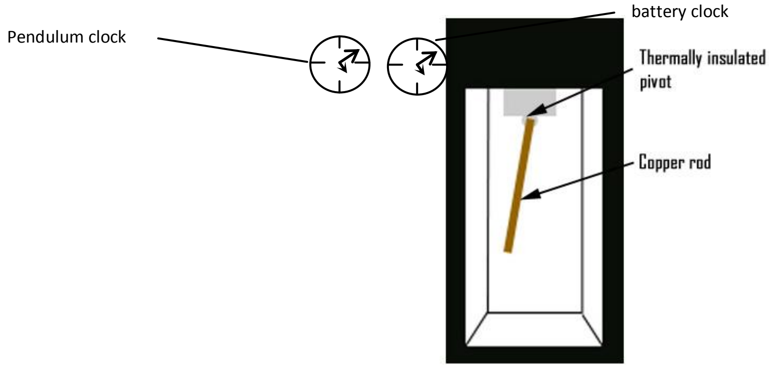
The invention takes advantage of the property of linear thermal expansion of a pendulum rod to measure the ambient temperature of the surroundings of the thermometer as the period of the pendulum changes.

Description:

When materials warm up, they also expand - train tracks have special joints to ensure that this doesn't become an issue.

The pendulum thermometer is designed to exploit this phenomenon. A pendulum swings with a regular period - this mechanism allows grandfather clocks to keep time, for instance. A pendulum's period is related to its length - longer pendulum, longer period.

So when the pendulum expands in length, the period of oscillation will change and the observer can hence measure the temperature.



The diagram above displays the intended design of the device, and indeed my prototype. Of course, for different purposes and different environments the scale and material may vary.

The pendulum rod is made of copper, and is 10cm in length. This length has to be calibrated at a given temperature, for which I suggest 0°C, to maintain convention with the Celsius scale.

Claim:

The pendulum thermometer has the following characteristics: (i) it can be used over a range of temperatures beyond the limits of normal thermometers (from absolute zero to just below the melting point of copper); (ii) it automatically gives a value for the *average* temperature between any two observations without the need for a complex recording device or repeated measurements and calculations. Therefore, I do not see it as replacing conventional thermometers, but rather as entirely complementary.

Patent #04-2011: The Johnson Converter

Inventor: Dr Philip Johnson
18 Stokes Road, Truro, Cornwall, TR1 5EJ

Abstract:

A device to harness solar energy. The sun heats a chamber of gas during the day which expands, driving a piston. At night the gas cools, and the process reverses.

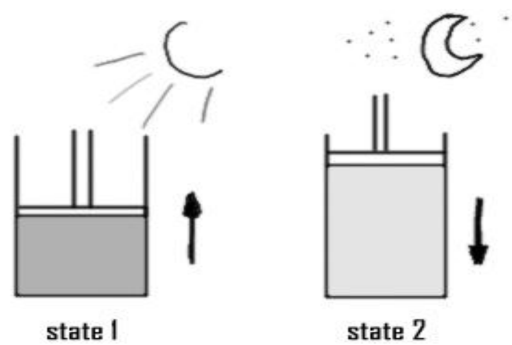
Description:

Every day over 1000 joules of energy beat down on every square metre of the Earth every second, most of it going to waste. The Johnson Converter intends to harness some of this energy, without the use of technically complex and fragile solar cells.

The Johnson Converter consists of a chamber of air – just plain air, so no poisonous gases, no special materials that cost extra money, or can be exhausted and need to be replaced – with a piston to extract the energy.

Essentially, the converter operates like a steam engine, but rather than the piston being driven by evaporating water, it's driven by expansion of gas due to insulation.

To the right is a schematic of the apparatus:



The cycle operates as follows:

Incoming solar energy heats the gas in the chamber, which expands isobarically. The walls of the chamber are fixed, and the piston is pushed upwards.

At night the gas cools and contracts, again isobarically, and the piston returns to its original position.

This cycle continues *ad infinitum* and a low, but steady, power is extracted by a dynamo.

Claim:

It is not anticipated that the Johnson Converter will replace traditional power stations, but with its ease of upkeep and relatively low setup cost, as well as the virtue it has of accessing otherwise wasted energy (and bringing down people's electricity bills), I believe that they will have a large market. Perhaps the government can be persuaded to give concessions to customers, who will be reducing dependency on fossil fuels, and aiding our efforts to meet the Kyoto Protocols.

Patent #05-2011: Feynman Ratchet

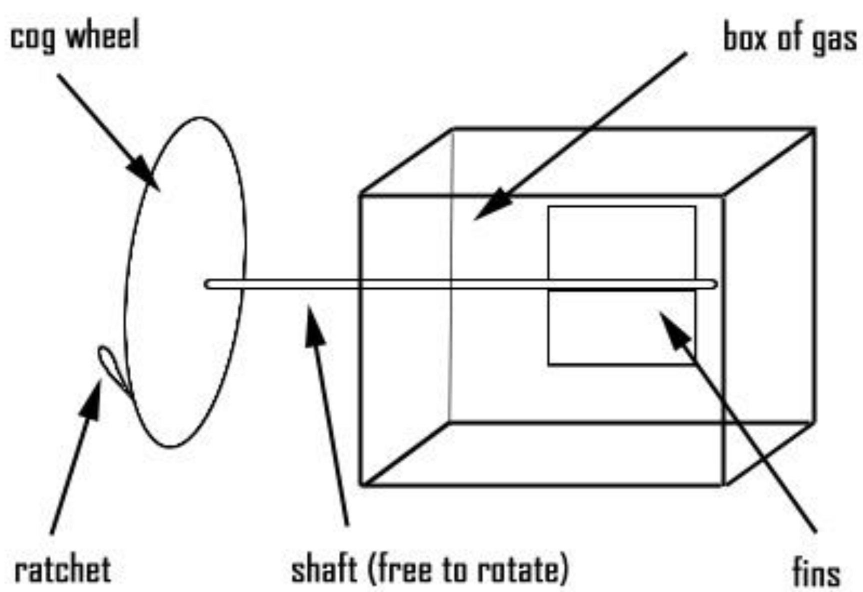
Inventor: Mr Thomas Vister
22 Dunvegan Road, Kingston-Upon-Hull, HU8 9PD

Abstract:

The ratchet extracts energy from the random motion of particles in the air, essentially providing a source of unlimited energy with no pollution.

Description:

Gas molecules are constantly in random motion (Brownian Motion) – witness how steam drifts away from a boiling kettle.



The device consists of a plate designed to intercept randomly moving gas particles. However, because of the teeth on the wheel it can only turn in one direction. Thus the random motion of the gas causes a rotation of the shaft and allows work to be extracted.

Claim:

The ratchet will theoretically be able to keep turning indefinitely, allowing a steady extraction of low power from the apparatus. In practice, eventually the shaft would be worn away, but for this apparatus to reach the point of mechanical failure would take many years. For all practical purposes, the ratchet would power low-load devices for their foreseeable lifetime.

Patent #06-2011: Instant Fridge

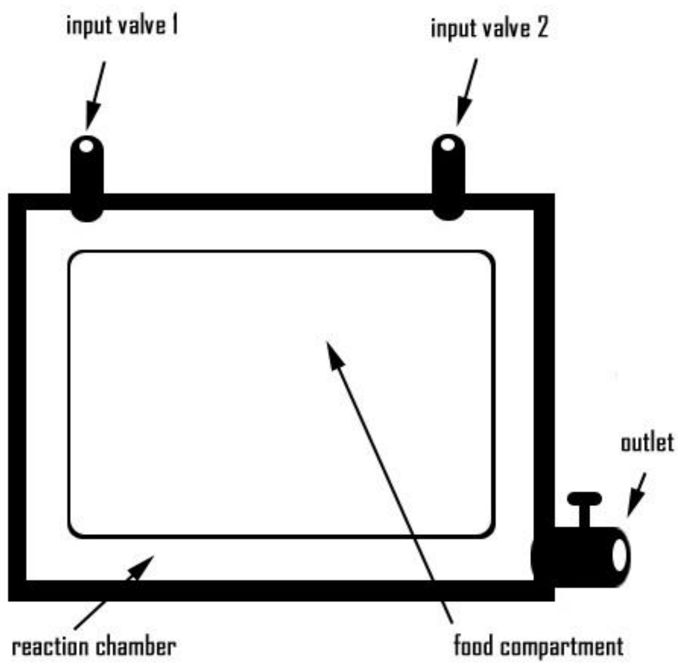
Inventor: Ms Amanda Ondengwe
17 Byron Road, Newport, NP20 3JQ

Abstract:

The Instant Fridge will allow rapid cooling of food and drink to a temperature suitable for serving.

Description:

If the chemicals ammonium chloride and barium hydroxide are mixed together, they react and draw in heat, rapidly cooling their surroundings.



I propose the apparatus described above. The two chemicals are introduced to the chamber, where they mix and react. As the box is thermally insulated, heat is drawn from the inner compartment, cooling the contents. The valve on the underside allows the chemical by-products to be drained and removed, ahead of future use.

Claim:

The instant fridge will serve to cool things quickly, for instance, a bottle of wine for serving. Alternatively it can be used to cool drinks or food when away from a refrigerator, where it acts a cool box with added functionality.

Patent #07-2011: Anodiser Art

Inventor: C Gane
17 Windrush Drive, Leicester

Abstract:

A layer of oxide can be deposited on the surface of titanium metal electrochemically, the thickness of the layer, and hence the resulting colour of the surface, being controlled by the anodising voltage. By masking the surface, or using magnetic fields, we can control the pattern of coloration. We propose to use this to mass produce simple and attractive key-rings.

Description:

The chemistry of anodisation of titanium in sulphuric acid is well understood. The use of strong acid can be hazardous and is preferably avoided. Instead an oxaline electrolyte can be used. The chemistry of the reaction, which requires a precise temperature of 48K, is too complex to be dealt with here, but the materials are less potentially harmful.

Claim:

The p.d. applied to the titanium anode determines the colour of the resulting surface. I find for example that a voltage of 5V gives a coating of TiO_2 of thickness 3×10^{-5} mm with a yellow appearance. Thus by suitable repeat masking we can build up an artistic pattern. To speed up the process, we propose the use of a variable potential across the surface, for example by the use of a magnetic field, to control the depth of the layer and hence the anodised pattern.

Suggested Deliverables

A short report on each patent that will:

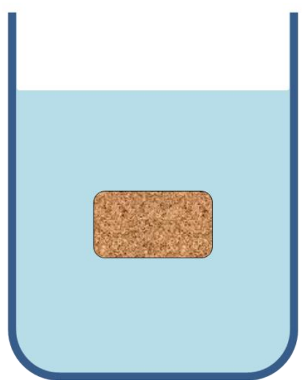
- Give a summary of how the device is supposed to work.
- State whether you believe a patent should be granted.
- Explain all the science required to understand the reasoning behind your decision.
- Explain your decision.
- Suggest improvements.

Where appropriate you may like to include specific data or discussion relating to your investigations.

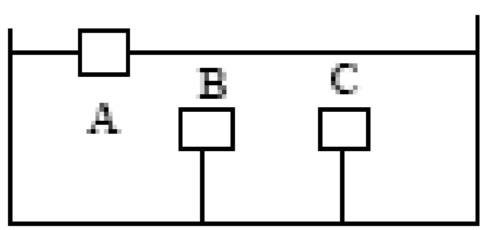
Questions for Class Discussion

Patent 1

1. What is specific gravity?
2. What range of values specific gravity are you likely to encounter in typical scenarios and why would knowing this range be useful?
3. How do you calculate the pressure of a liquid in a closed container? (Assume the container is completely filled with the liquid).
4. How do you calculate the pressure in a free standing fluid?
5. What equation defines the Bulk Modulus of a substance? Why does it have a minus sign?
6. A cork, weighing 1 g, is submerged in a beaker of water. Draw the forces acting on the cork. Given that kg m^{-3} and kg m^{-3}, what happens if the cork is let go? What is this an example of?



7. Consider the following set-up:

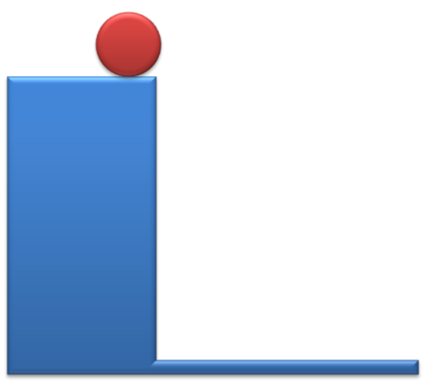


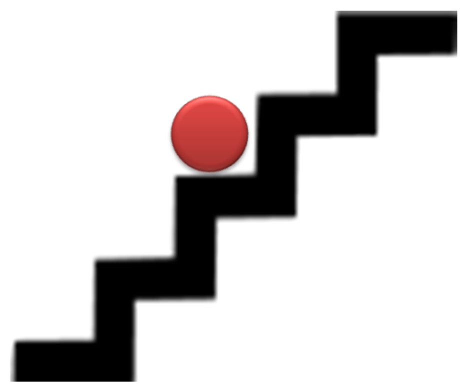
a) The blocks all have the same shape and size.
b) Mass of block A = mass of block B.
c) Mass of block B < mass of block C.

Is the buoyant force of A greater than/less than/equal to the buoyant force on B?
Is the buoyant force of A greater than/less than/equal to the buoyant force on C?
Is the buoyant force of B greater than/less than/equal to the buoyant force on C?

Patent 2

1. Explain the concept of potential energy in general terms.
2. What is the difference between a ‘conservative’ and ‘non-conservative’ force? Define each type of force in *your own words*.
3. Provide examples of a conservative and non-conservative force.
4. What do we mean by a closed and open system in this context?
5. What is the general formula for potential energy when a conservative force is exerted on an object?
6. Consider the specific cases of gravitational potential energy (GPE) and elastic potential energy (EPE); that are the conservative forces involved in each case and how would you define them algebraically?
7. What are the equations for GPE and EPE? Can you derive them from first principles?
8. In the following diagrams where would you set PE to be zero and why?

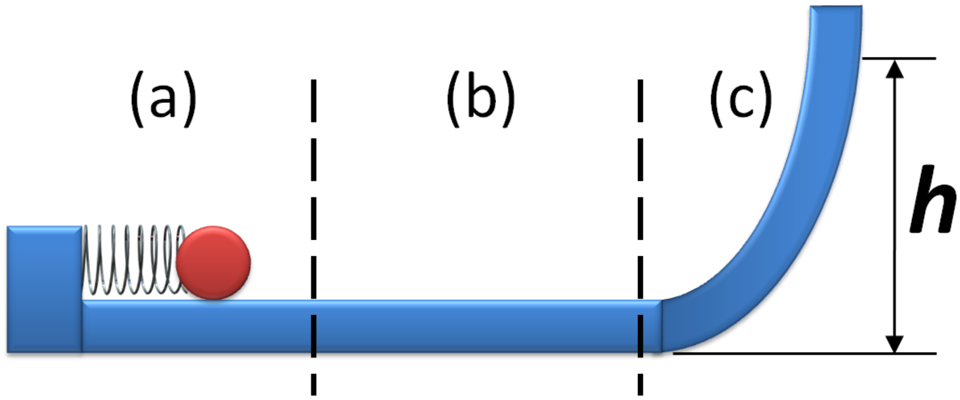




The springs in these two diagrams are not at their full extension.

9. Consider a closed system. A conservative force acts on an object within the system and increases that object’s kinetic energy. What happens to the system’s potential energy?

10. Consider the following diagram:

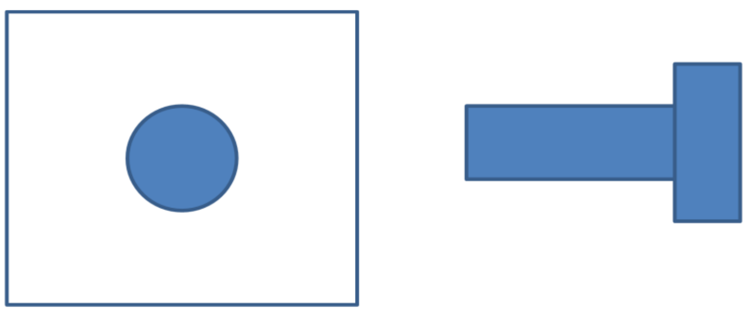


a) A ball is pushed against a spring that has a force constant, k, of 175 Nm^{-1} compressing the spring by 8 cm. How much EPE is stored in the system?
b) The ball is then released and it travels along the frictionless portion of the horizontal track. What is its maximum velocity if it has a mass of 5 kg?
c) The ball then travels up a curved portion of the track. What vertical height, *h*, does the ball reach before it momentarily comes to rest?

11. Why does it often seem like mechanical energy is not conserved in ‘real world’ situations? How can we explain this physically?

Patent 3

1. In your *own words* define the zeroth law of thermodynamics.
2. How are the coefficients of linear and volume expansion defined?
3. How would you calculate the change in length, or volume, of an object when it is heated?
4. How is the coefficient of volume expansion numerically related to the coefficient of linear expansion?
5. The bolt will not quite fit through the circular hole in the plate. Explain why heating the plate will allow the bolt to pass through.



6. When does simple harmonic motion occur?
7. In your own words provide a definition for simple harmonic motion.
8. Consider a weight attached to a spring. What force is acting to produce SHM? Why does it have a negative sign?
9. How is the frequency of the oscillation related to its period? What units are each of these quantities measured in?
10. What is the equation for the position of an object undergoing SHM? What do all of the algebraic quantities relate to?
11. Using differentiation with respect to time calculate the velocity and acceleration of an object undergoing SHM.
12. What is the relationship between displacement and acceleration for an object undergoing SHM?
13. If the force producing SHM is provided by a spring how does angular frequency relate to spring constant?
14. From first principles calculate the potential and kinetic energy in SHM. What is the total energy at any given time?
15. Consider a simple pendulum. What is the period of the oscillation dependant on and why?

Patent 4

1. State Boyle's Law
2. Boyle's Law can be modified to include temperature to give . What are algebraic quantities in this equation?
3. The equation given above can be modified to form the Ideal Gas Law. State the Ideal Gas Law. What substitutions/conversions were used to change the equation above into the Ideal Gas Law?
4. If you double the pressure of an ideal gas and quadruple its temperature how does its volume change?
5. How can you calculate the density of an ideal gas?
6. Considering the microscopic properties of a gas how would you calculate, from first principles, the pressure exerted by a gas on its container?
7. Why is the average kinetic energy of a molecule of gas − rather than − ?
8. What is the root mean square (rms) speed of a molecule of gas?
9. What is the equipartition theorem?
10. What do we mean by 'mean free path' and how can you calculate it in an ideal gas?
11. What is the difference between heat and temperature?
12. When we consider heat flow what is the difference between *C, c'* and *c*?
13. What unit of energy did heat used to be measured in and what unit is it now measured in? Why was this change adopted? How can you convert between the two units?
14. The quality of a good pint of lager is highly dependent on temperature. The brewery states that their lager should be served at an optimum of 2^{o}C and certainly no higher than 6^{o}C. However, the bar tender pours your pint, which comes out of the cooled pump at 1.5^{o}C, into a glass that has just come out of the dishwasher at 58^{o}C. What temperature will your pint be and will it be acceptable according to the breweries standards?
15. What is a phase change (as related to thermodynamics)?
16. Why does the temperature of a substance remain constant during a change of state?
17. What are the equations that are associated with a change in state from solid to liquid and liquid to gas?
18. An artist wants to cast a solid gold statue, weighing 425 g. How much heat is required in order to complete melt the gold so that it can be poured into the mold?
19. State, in your own words, the First Law of Thermodynamics.
20. What is a quasi-static process and how does it approximate an idealized process?

21. What is a PV diagram and what is it used for?

22. A gas has an initial pressure (P_1) equal to 10 atmospheres and an initial volume (V_1) of 5 m^3. The gas then undergoes an isothermal expansion such that its new volume, V_2, is twice that of V_1. It then undergoes an isobaric expansion to a new volume, V_3, that is four times that of V_1. Draw these processes on a PV diagram. How can you calculate the work done by the gases at the end of these two processes?

23. Why is the heat capacity at constant volume of a gas less than the heat capacity at constant pressure?

24. How are C_P and C_V related and what are their theoretical values for a monatomic gas?

25. Most solids have molar heat capacities approximately equal to $3R$; why is this?

26. Why does the equipartition fail in some cases?

27. What is an adiabatic process?

28. How can you calculate the work done during an adiabatic process?

Patent 5

1. What is the Maxwell-Boltzmann speed distribution function?
2. What is the most probable speed, v_{max}, of a molecule in a Maxwell-Boltzmann distribution?
3. State, in your own words, the Second law of Thermodynamics.
4. Draw a schematic representation of a heat engine.
5. How can you calculate the efficiency of a heat engine? Is it possible for a heat engine to have an efficiency of 100%?
6. How does a refrigerator work?
7. What is entropy and how to we define the change in entropy of a system?
8. How does the entropy of the universe change during a reversible and an irreversible process?
9. Rephrase the Second Law of Thermodynamics with reference to entropy.

Patent 6

1. What determines how quickly a chemical process occurs?
2. Why can temperature have an effect on reaction rate?
3. How can the rate constant of a process be measured experimentally?
4. Why do some reactions proceed quicker than others?
5. What is meant by reaction order?
6. How can reaction order be determined experimentally? What are integrated rate laws?
7. How can we determine the half-life of a chemical process?
8. What is the steady-state approximation?
9. What is the significance of the rate determining step?
10. How can kinetic data be used to derive a reaction mechanism?
11. What is the significance of the first law of thermodynamics to chemical processes? How can it be applied to real chemical processes?
12. What is the significance of equilibrium in the context of a chemical process?
13. What is an equilibrium constant?
14. How much work is done when 1.00 kg of water (volume = 1×10^{-3} m^3) is converted to steam (volume = 1.671 m^3) at 100˚C and standard atmospheric pressure? How much energy must be added to this system to achieve this change?
15. How can the amount of work a chemical process can do be calculated?
16. What is the definition of enthalpy (both in terms of a mathematical and qualitative description)?
17. What are exothermic and endothermic processes?
18. What does an energy profile look like for an endothermic or exothermic process?
19. How can the heat and energy changes of a chemical process be measured?
20. What are heat capacities and what is the significance of a specific heat capacity?
21. What is meant by the term 'spontaneous chemical process?
22. If a ball is at rest on a floor, is it possible for it to start bouncing spontaneously? If it is possible, how likely is it to occur?
23. Why is disorder an important consideration in chemical thermodynamics?
24. How can we quantify the entropy of a system?
25. How can we calculate the entropy change of a process (e.g. a phase change)?
26. How does entropy vary with temperature?
27. What is the Gibb's Free Energy and how is it related to the enthalpy and entropy of a process?
28. How can the spontaneity of a process be determined simply from its equilibrium constant?

Patent 7

1. Compare the electrical conductivity of a pure water, a solution of sugar in water and a solution of salt in water? Why do they vary?
2. What are oxidation and reduction processes in terms of electron exchange?
3. What is a redox process?
4. How can a redox process be used to do work?
5. What is the difference between a Galvanic and an Electrolytic cell? Draw diagrams of both?
6. What are standard reduction potentials?
7. What is a half-cell? How are half-cells combined? How is the overall cell potential calculated?
8. How can the maximum work that the cell can do (and hence the Gibb's energy change) be calculated from a cell potential?
9. What is the Nernst equation? How is it used?
10. What is meant by the *phase* of a wave
11. What is meant by coherence? Can waves of different wavelength be coherent?
12. A wave enters a glass block of thickness b at normal incidence. What is the phase change in passing through the block?
13. If the ray is reflected at the bottom surface what is the phase change on emerging from the top surface of the block?
14. What is the phase change of a ray reflected at the top surface?
15. Why do fringes form when monochromatic light is reflected from a thin film of water on a glass surface? What is the effect in white light?
16. White light reflected normally from a thin film of oil (refractive index 1.2) appears yellow (wavelength around 600nm). What is the thickness of the oil film?
17. In Young's slits experiments as the slits are separated does the interference pattern;

    a) Becomes more compressed.
    b) Becomes more spaced out.

Individual Exercises

Patent 1

1. A robber throws a bar of gold out of his get-away boat into a lake (to be retrieved later when the police are not in pursuit). Describe and explain the change in the height of the water level on the lake.

2. A helium balloon (with an elastic skin) is released into the atmosphere. Describe and explain the subsequent behaviour.

Patent 3

3. By applying Newton's second law, and using the approximation $\sin \theta \approx \theta$, show that for small displacements the angle to the vertical of a simple pendulum bob satisfies the equation of simple harmonic motion (SHM):

   – .

   Verify that a solution of this equation is where $\omega^2 = g/l$. What is the period of the pendulum?

4. The aluminium skin of Concorde rose to around 420 K in supersonic travel. How much extra leg room could this create?

Patent 4

5. (a) If 300J of energy in the form of heat is absorbed by a system and the system does 200J of work on the surroundings, what is ΔU for the system?

   (b) A chemically reacting mixture of hydrogen and oxygen loses 550J of heat to the surroundings and does 240J of work as the gas mixture expands. What is the change in the internal energy of the system in joules?

6. The specific heat of a mole of a gas at constant volume C_V is the heat required to raise the temperature by 1 degree: so $C_V = \dfrac{\Delta Q}{\Delta T}$ at constant volume. Similarly C_P is defined at constant pressure. Use the first law of thermodynamics in the form $\Delta U = \Delta Q + \Delta W$ together with the perfect gas law and an expression for ΔW, to show that for a perfect gas $C_P - C_V = R$ (the gas constant).

7. What is the ratio of the typical (modal) speeds of hydrogen and oxygen molecules in the Earth's atmosphere at STP?

8. An adiabatic change is defined as a change of state with no exchange of heat (i.e. a change in internal energy is the result of doing work). Show that for an adiabatic change PV^{γ} = constant, where $\gamma = C_P/C_V$.

   [Hint: start from the first law in the form $\Delta U = \Delta Q + \Delta W$ with $\Delta U = C_V\Delta T$, and use with the perfect gas law and an expression for ΔW, together with the result of question 7.]

9. A monatomic gas and a diatomic gas at the same initial temperature and pressure undergo an adiabatic contraction to half the original volume. What is the ratio of pressures in the final states. What is the ratio of temperatures? Explain the difference.

10. The energy transfer between the system and the surroundings, in the form of heat at constant pressure, is described by which of the following symbols?

    ΔS, ΔP, ΔH, ΔU, ΔT.

    Define the meaning of the other symbols.

11. What are the steps in a Carnot Cycle?

12. Why is the Carnot Engine/Cycle important and why cannot it be achieved in real life?

13. How can you calculate the Carnot efficiency?

Patent 6

14. Define the term 'oxidation number' for an atom.

    What is the oxidation state of:

    a) Gold in $[AuCl_4]^-$,
    b) Nickel in $Ni(NO_3)_2$
    c) Nitrogen in $Ni(NO_3)_2$?

15. What does the subscript denote in each of these types of changes in reaction enthalpy?

    $\Delta_r H$, $\Delta_c H$, $\Delta_f H$, $\Delta_{sol} H$, $\Delta_v H$.

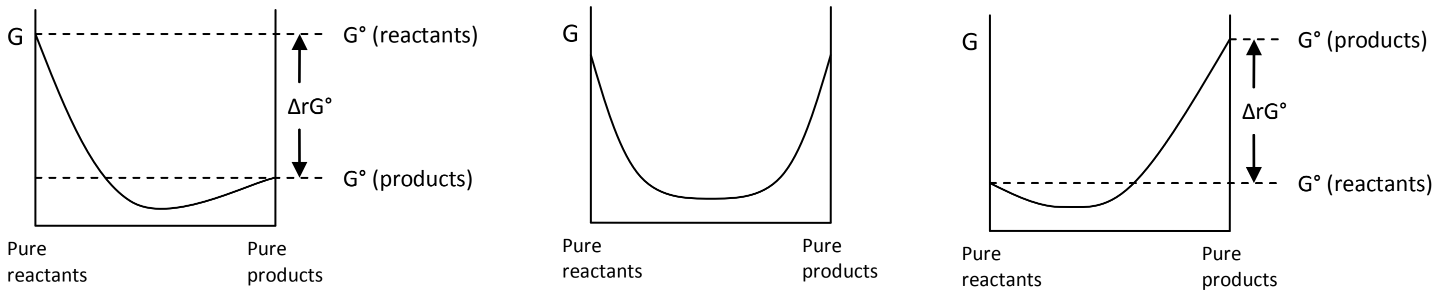
16. Calculate the standard enthalpy change for the reaction:

    $$CO(g) + \tfrac{1}{2} O_2(g) \rightarrow CO_2(g)$$

    given

    a) $C(s) + O_2(g) \rightarrow CO_2(g)$ $\Delta H = -393.5\ \text{kJ mol}^{-1}$
    b) $C(s) + \tfrac{1}{2}O_2(g) \rightarrow CO(g)$ $\Delta H = -110.5\ \text{kJ mol}^{-1}$

17. What is the position of chemical equilibrium represented by the following diagrams?



18. Calculate the standard free-energy change for the following reaction at 298K:

$Na(s) + H_2O(l) \rightarrow NaOH(aq) + \frac{1}{2}H_2(g)$

given

$\Delta_f G°\,[Na^+(aq)] = -261.87$, $\Delta_f G°\,[OH^-(aq)] = -157.3$,

$\Delta_f G°\,[H_2O(l)] = -\ 237.19\ kJ\ mol^{-1}$.

19. Consider the ammonia synthesis reaction

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

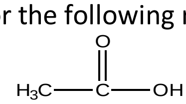
$\Delta G° = -33.3\ kJ\ mol^{-1}$ at 25°C.

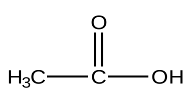
For each of the following mixtures of reactants and products at 25°C predict the direction in which the system will shift to reach equilibrium.

a) $P_{NH3} = 1.00$ atm $P_{N2} = 1.47$ atm $P_{H2} = 1.00 \times 10^{-2}$ atm.

b) $P_{NH3} = 1.00$ atm $P_{N2} = 1.00$ atm $P_{H2} = 1.00$ atm.

20. Calculate $\Delta H°$, $\Delta S°$ and $\Delta G°$ for the following reactions that both produce acetic acid:

a) $CH_4(g) + CO_2(g) \rightarrow$  (l)

b) $CH_3OH(g) + CO\ (g) \rightarrow$  (l)

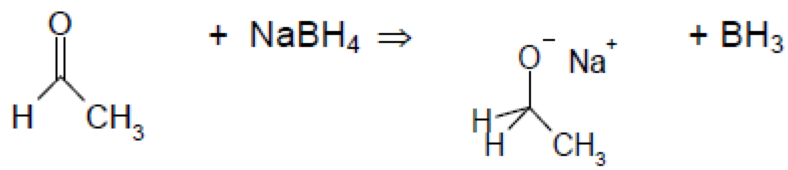
Which reaction would you choose as a commercial method for the production of acetic acid? What temperature conditions would you choose for the reaction? Assume standard conditions and assume ΔH° and ΔS° are temperature independent.

21. At 25°C for the reaction:

$2NO_2(g) \rightleftharpoons N_2O_4(g)$

The values of $\Delta H°$ and $\Delta S°$ are $-58.03\ kJ\ mol^{-1}$ and $-176.6\ J\ K^{-1}\ mol^{-1}$ respectively. Calculate the value of the equilibrium constant at 25°C. Assuming $\Delta H°$ and $\Delta S°$ are temperature independent, estimate the value of K at 100°C.

22. In this reaction, identify which species is being reduced and which is oxidised:



23. Give an expression for the solubility of $PbBr_2$ in water at equilibrium. Using this expression, calculate the maximum concentration of the salt in water (K = 4.6 x 10^{-6} mol^3 dm^{-9}).

24. The gas PCl_5 decomposes at elevated temperatures to produce PCl_3 and Cl_2 gases. Given the equilibrium partial pressures below, calculate the equilibrium constant and use it to determine the initial amount of PCl_5 required to give an equilibrium concentration of 0.65 bar at the same temperature.

P_{PCl_5} = 0.051 bar P_{PCl_3} = 0.602 bar P_{Cl_2} = 0.602 bar

25. The Haber process is used to produce ammonia from nitrogen and hydrogen on an industrial scale and the following equilibrium concentrations were found at 127°C. Calculate the equilibrium constant at this temperature. What temperature and pressure regions would yield the most ammonia?

$N_2 + 3\,H_2 \leftrightarrows 2\,NH_3$ $\Delta H = -92$ kJ mol^{-1}
$[N_2]$ = 0.289 mol dm^{-3}
$[H_2]$ = 0.049 mol dm^{-3}
$[NH_3]$ = 1.136 mol dm^{-3}

Patent 7

26. a) Which electrode of a voltaic cell, the cathode or the anode, corresponds to the higher potential energy for the electrons?
b) What are the units for electrical potential? And how does this unit relate to energy expressed in joules?
c) What is special about the *standard* cell potential?

27. a) Write the half-reaction that occurs at a hydrogen electrode in acidic aqueous solution when it serves as the anode of a voltaic cell.
b) The platinum electrode in a standard hydrogen electrode is specially prepared to have a large surface area. Why is this important?
c) Sketch a standard hydrogen electrode.

28. a) Why is it impossible to measure the standard reduction potential of a single half-reaction?
b) Describe how the standard reduction potential of a half-reaction can be determined?
c) By using the data provided in appendix E, *Chemistry the central science*, Brown 10th edition p.1128, determine which is the more unfavourable reduction, Cd^{2+}(aq) to Cd(s) or Ca^{2+} to Ca(s)?

29. A voltaic cell that uses the reaction;

$PdCl_4^{2-}(aq) + Cd(s) \rightarrow Pd(s) + 4Cl^{-}(aq) + Cd^{2+}(aq)$,

has a measured standard cell potential of +1.03 V.

a) Write the two half-cell reactions.
b) By using the data from appendix E of Chemistry, The Central Science, 10th ed. Brown, Lemay and Bursten, (p.1128) Standard reduction potentials at 25°C. Determine Eored for the reaction involving Pd.
c) Sketch the voltaic cell, label the anode and cathode, and hence indicate the direction of electron flow.

30. Using the data in appendix E of *Chemistry, The Central Science*, 10th ed. Brown, Lemay and Bursten (p.1128) *Standard reduction potentials at 25°C*. Calculate the standard emf for each of the following reactions;
   a) $H_2(g) + F_2(g) \rightarrow 2H^+(aq) + 2F^-(aq)$
   b) $Cu(s) + Ba^{2+}(aq) \rightarrow Cu^{2+}(aq) + Ba(s)$
   c) $3Fe^{2+}(aq) \rightarrow Fe(s) + 2Fe^{3+}(aq)$
   d) $Hg_2^{2+}(aq) + 2Cu^+(aq) \rightarrow 2Hg(l) + 2Cu^{2+}(aq)$

31. Given the following half-reactions and associated standard reduction potentials;
   (1) $AuBr_4^-(aq) + 3e^- \rightarrow Au(s) + 4Br^-(aq)$ $E^o_{red} = -0.858$ V
   (2) $Eu^{3+}(aq) + e^- \rightarrow Eu^{2+}(aq)$ $E^o_{red} = -0.43$ V
   (3) $IO^-(aq) + H_2O(l) + 2e^- \rightarrow I^-(aq) + 2OH^-(aq)$ $E^o_{red} = +0.49$ V
   (4) $Sn^{2+}(aq) + 2e^- \rightarrow Sn(s)$ $E^o_{red} = -0.14$ V

   a) Write the cell reaction for the combination of these half-cell reactions that leads to the largest positive cell emf, and calculate the value.
   b) Write the cell reaction for the combination of half-cell reactions that leads to the smallest positive cell emf, and calculate the value.

32. Acetylene gas, $C_2H_2(g)$ is used in welding.
   a) Write a balanced equation for the combustion of acetylene gas to $CO_2(g)$ and $H_2O(l)$.
   b) How much heat is produced in burning a mole of C_2H_2 under standard conditions if both reactants and products are brought to 298K? Thermodynamic parameters can be found in appendix C of *Chemistry, The Central Science*, 10th ed. Brown, Lemay and Bursten (p. 1123). *Thermodynamic Quantities for Selected Substances at 298.15K (25°C)*
   c) What is the maximum amount of useful work that can be accomplished under standard conditions by this reaction?

33. Two waves —— and —— interfere. Show that the intensity of the interference pattern is proportional to − .
(The intensity of a wave is proportional to the square of the amplitude.)

34. Two narrow slits separated by 1 mm are illuminated by light of wavelength 500 nm and the interference pattern is observed on a screen 2m away. Calculate the number of bright fringes per cm on the screen.

35. a) A film of oil of refractive index 1.45 rests on an optically flat glass surface of refractive index 1.6. White light at normal incidence is reflected predominantly at 690 nm and 460 nm. What is the thickness of the film?
   b) If instead the film of oil floats on water (refractive index 1.33) the light is reflected predominantly at 700 nm and 500 nm. What is the thickness of the film in this case?