ME 266 THERMODYNAMICS 1

ENERGY, WORK AND HEAT

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ENERGY, WORK AND HEAT

Energy

- A system may posses several types of energy:
  - ✓ Kinetic Energy: $K.E = \frac{1}{2} mV^2$
  - ✓ Potential Energy: $P.E = m.g.h$
  - ✓ Internal Energy: U

The **Internal Energy** is the energy associated with the translation, rotation, and vibration of the molecules, electrons, protons, and neutrons, and the chemical energy due to bonding between atoms and between subatomic particles.

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Conservation of Energy

- ✓ The law of ***conservation of energy*** states that the energy of an isolated system **remains constant**.
- ✓ Energy cannot be created or destroyed in an isolated system; it can only be transformed from one form to another.

$$KE + PE + U = Constant$$

$$\frac{mV^2}{2} + mgh + U = Constant$$

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WORK

- **Work**, designated ***W***, is often defined as the product of a force and the distance moved in the direction of the force: the mechanical definition of work.

- Thermodynamic work (a broader sense of work) is done by a system if the sole external effect on the surroundings could be the raising of a weight.

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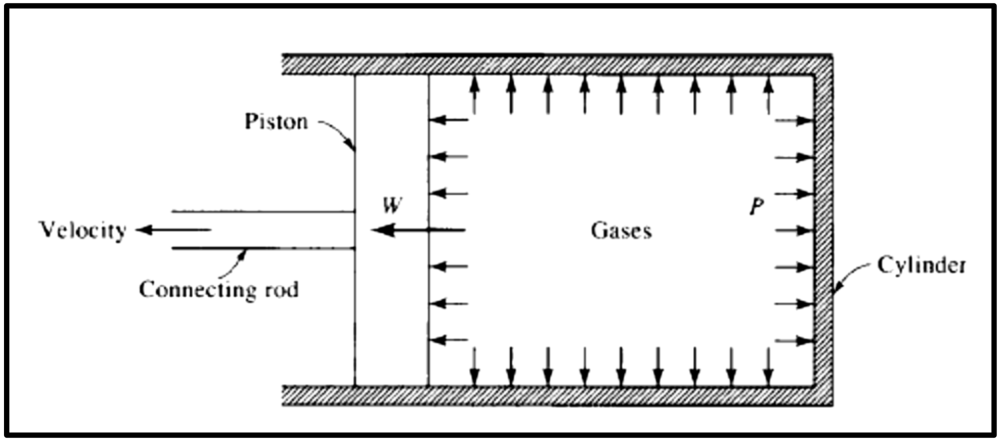
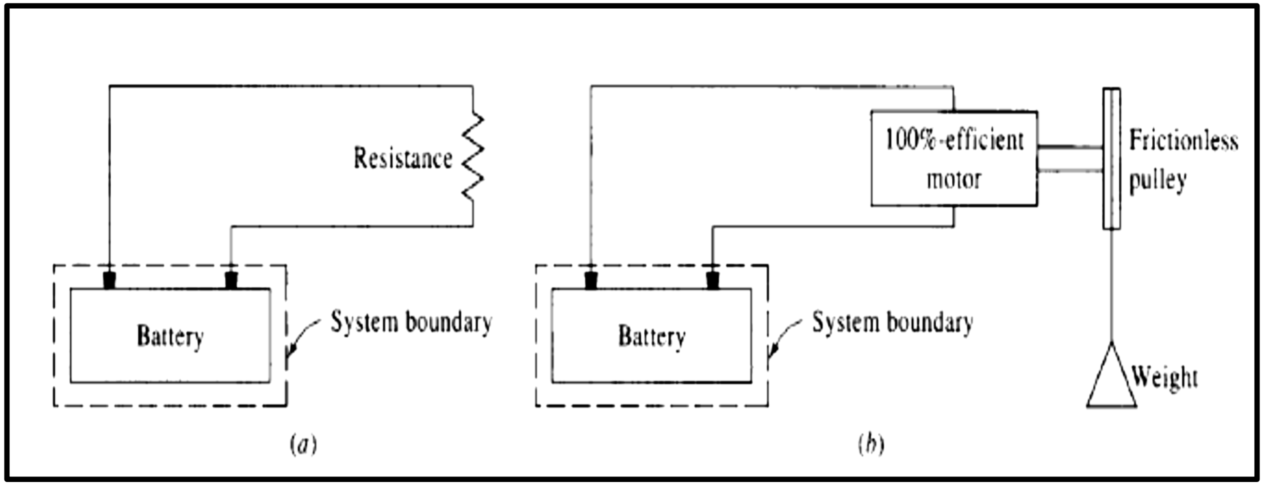
Work





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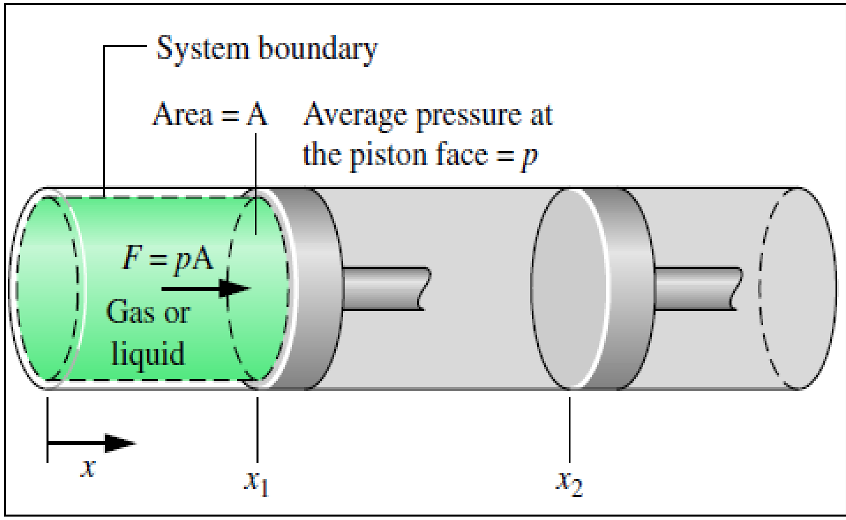
Sign Convention

Work is +ve if done on the surroundings

Work is -ve if done on the system by the environment

Example

*A piston compressing a fluid is doing **negative** work on the system, whereas a fluid expanding against a piston is doing **positive** work.*



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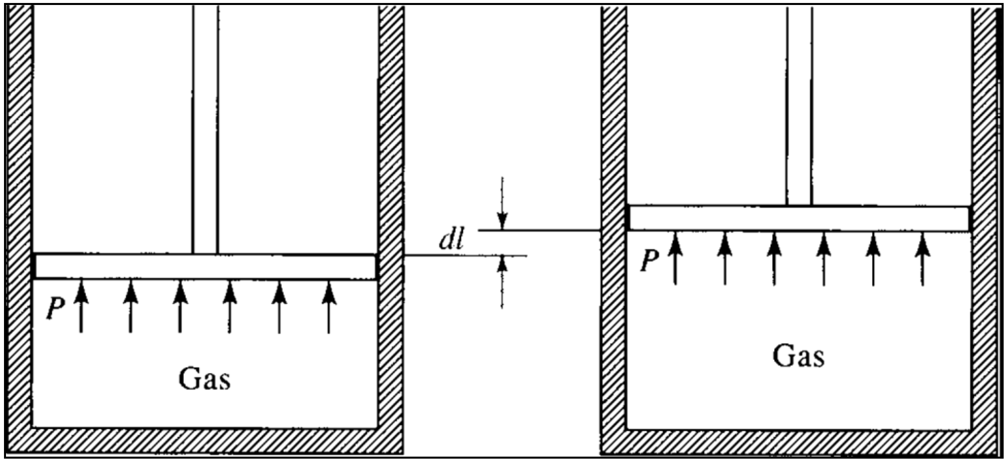
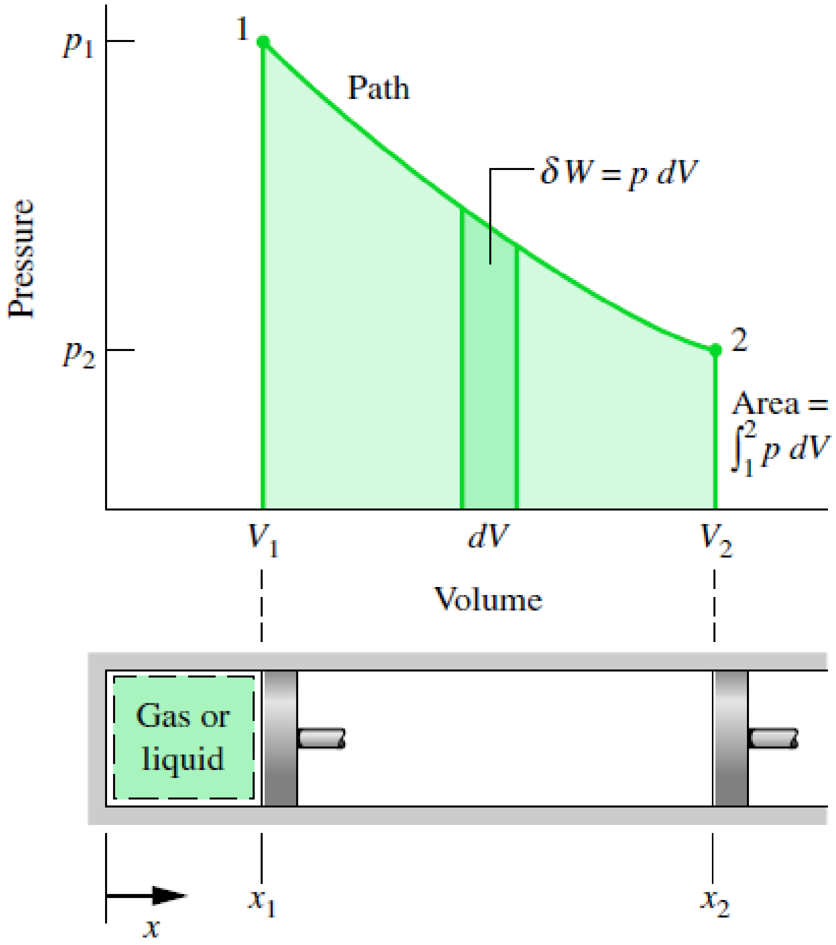
Expansion Work



$$\delta W = PAdl \quad or \quad \delta W = PdV$$

$$W_{1-2} = \int_{V_1}^{V_2} PdV$$



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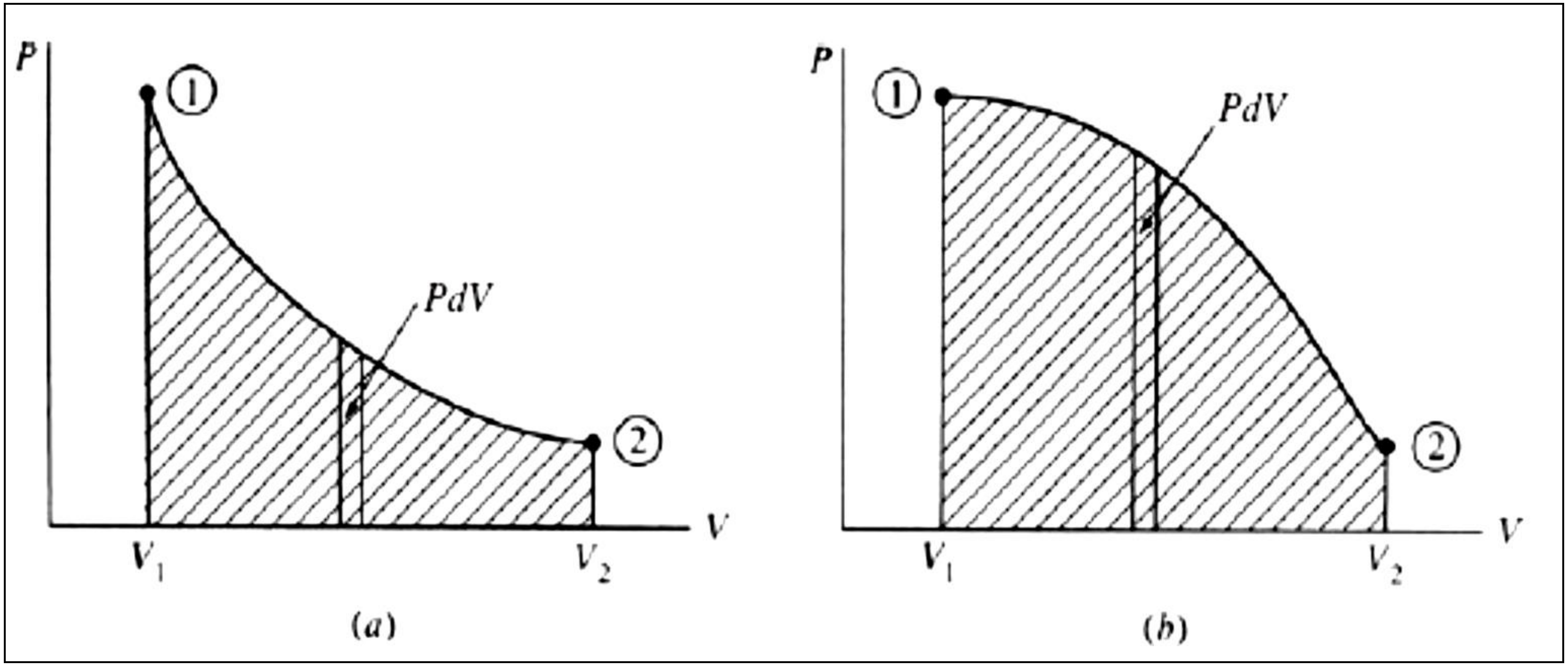
Work as a Path Function



Analysis of *PdV* Work

$$W_{1-2} = \int_{V_1}^{V_2} P dV$$

To evaluate this integral analytically, one has to establish a relationship between *P* and *V* during the expansion or compression process. Typically, the relation is given as:

$$PV^n = Constant$$

A quasi-equilibrium process described by such an expression is called a ***polytropic process***, n is the **polytropic index**, and is constant for a given process.

Analysis of *PdV* Work

$$PV^n = Constant$$

When:

- ✓ **n=0:** P=constant i.e. isobaric process
- ✓ **n=1:** PV=constant, which is an isothermal process for a perfect gas
- ✓ **n=∞**: results in V=constant i.e. isochoric (Proof??)
- ✓ **n=ϒ**: which is a reversible adiabatic process for a perfect gas.

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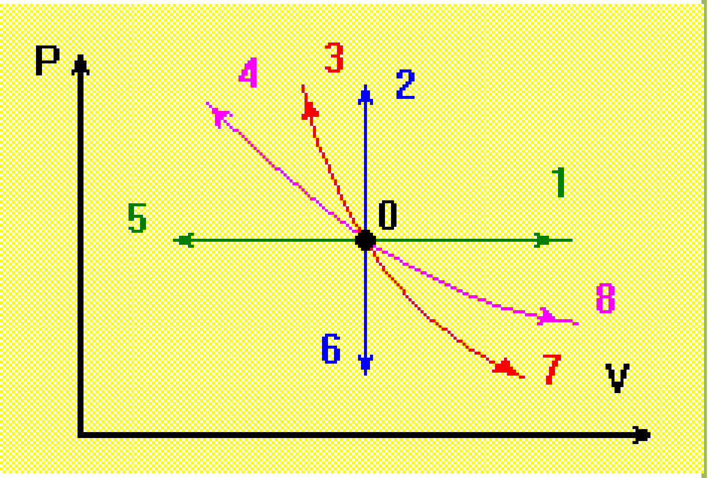
Analysis of *PdV* Work

$$PV^n = constant$$



0 to 1= constant pressure heating,
0 to 2= constant volume heating,
0 to 3= reversible adiabatic compression,
0 to 4= isothermal compression,
0 to 5= constant pressure cooling,
0 to 6= constant volume cooling,
0 to 7= reversible adiabatic expansion,
0 to 8= isothermal expansion.

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Analysis of *PdV* Work

$$\boxed{PV^n = constant}$$

$$W = \int_{V_1}^{V_2} PdV \quad = \int_{V_1}^{V_2} \frac{Constant}{V^n} dV$$

$$= \frac{(Constant)V_2^{1-n} - (Constant)V_1^{1-n}}{1-n}$$

$$Constant = P_1V_1^n = P_2V_2^n$$

$$= \frac{(P_2V_2^n)V_2^{1-n} - (P_1V_1^n)V_1^{1-n}}{1-n} = \frac{P_2V_2 - P_1V_1}{1-n}$$

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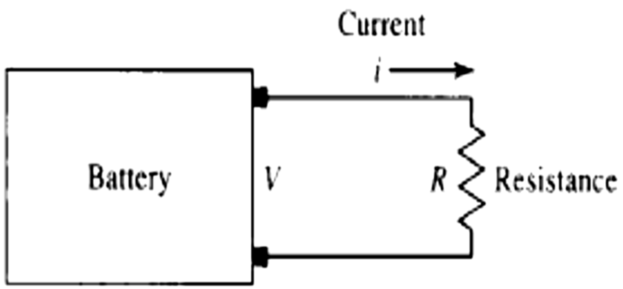
Other work modes: Electrical Work



Rate of Electrical Work (Power), W

$$\dot{W} = Vi$$

Electrical Work , J, over Δt is:

$$W = Vi\Delta t$$

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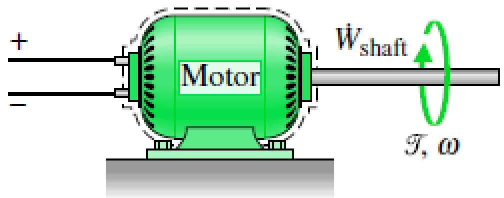
Other work modes: Shaft work



Power transmitted from shaft to surroundings is:

$$\dot{W} = F_t V = (\mathcal{T}/R)(R\omega) = \mathcal{T}\omega$$

$$\mathcal{T} = F_t R$$

$$V = R\omega$$

tangential force F_t *and radius* R; velocity at the point of application of the force is $V = R\omega$,
ω is the angular velocity.

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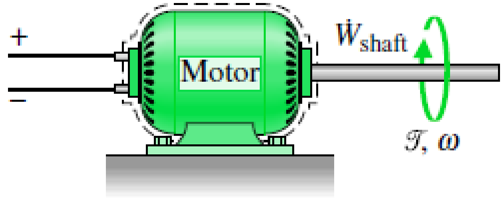
Other work modes: Shaft work



The work transferred in a given time t is given by

$$W = T\omega\Delta t$$

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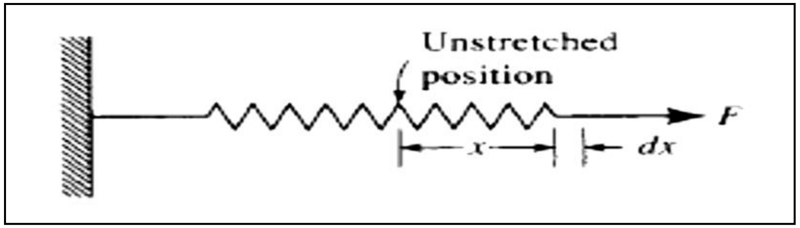
Other work modes: Spring work



The work necessary to stretch a linear spring with spring constant *K* from a length x_1 to x_2 can be found by using the relation for the force:

$$F = Kx$$

$$W = \int_{x_1}^{x_2} F\,dx = \int_{x_1}^{x_2} Kx dx = \frac{1}{2}K(x_2^2 - x_1^2)$$

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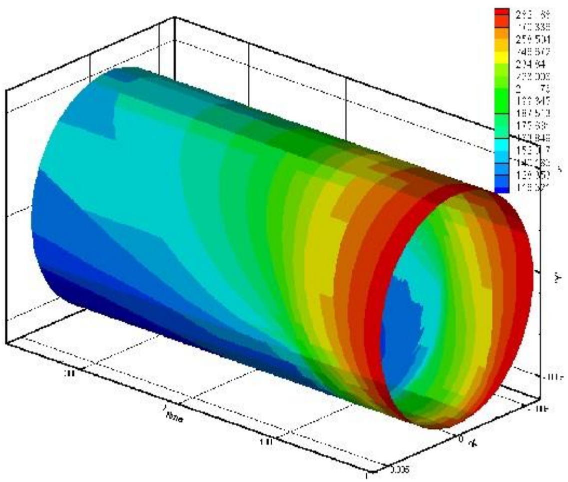
HEAT

- ✓ Heat is energy transferred across the boundary of a system due to a difference in temperature between the system and the surroundings of the system.
- ✓ A process in which there is zero heat transfer is called an *adiabatic process*.



SIGN CONVENTION

- ✓ Heat transfer to system: +ve
- ✓ Heat transfer from system: -ve

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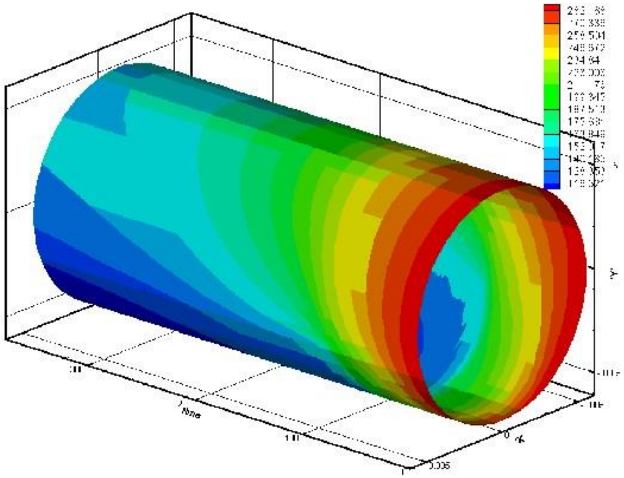
HEAT

- There are three heat transfer modes: *conduction, convection, and radiation*
- **Heat is a path function** and is usually denoted as Q



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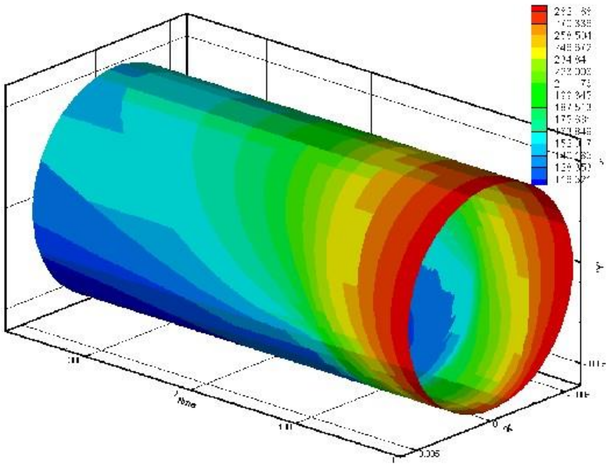
HEAT



RECALL

- ✓ The unit for energy, both as heat and work is the Joule (J).
- ✓ The rate of transfer (of heat or work) is measured in J/s or W, which is Power.

Question 1

A **2200-kg** automobile traveling at **90 km/h (25 m/s)** hits the rear of a stationary, **1000-kg** automobile. After the collision the large automobile slows to **50 km/h (13.89 m/s)**, and the smaller vehicle has a speed of **88 km/h (24.44 m/s)**. What has been the increase in internal energy, taking both vehicles as the system?

The kinetic energy before the collision is:

$$\mathrm{KE}_1 = \frac{1}{2}\mathrm{m_a}{\mathrm{V_a}}^2$$
$$= \frac{1}{2} \times 2200 \times 25^2$$
$$= 687\ 500\ \mathrm{J}$$

After the collision the kinetic energy is:

$$\mathrm{KE}_2 = \frac{1}{2}\mathrm{m_a}{\mathrm{V_a}}^2 + \frac{1}{2}\mathrm{m_b}{\mathrm{V_b}}^2$$
$$= \frac{1}{2} \times 2200 \times 13.89^2 + \frac{1}{2} \times 1000 \times 24.44^2$$
$$= 510\ 900\ \mathrm{J}$$

The conservation of energy requires that:

$$E_1 = E_2 \quad or \quad KE_1 + U_1 = KE_2 + U_2$$

$$U_2 - U_1 = KE_1 - KE_2$$

$$= 687\ 500 - 510\ 900 = 176\ 600\ \mathrm{J}$$

Question 2

The drive shaft in an automobile delivers **100 N.m** of torque as it rotates at **3000 rpm**. Calculate the power transmitted.

The power (or work rate) is found from the expression:

$$P = T\omega$$

Where:

T is torque and **ω** is angular velocity expressed in rad/s

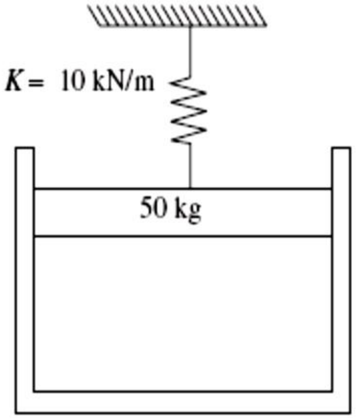
$$\omega = 3000 \times \frac{2\pi}{60} = 314.2\, rad/s$$

$$P = T\omega = 100 \times 314.2 = 31\,420\, \boldsymbol{W}$$

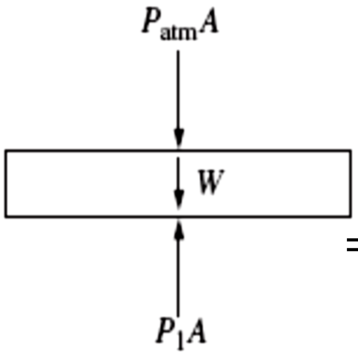
$$\mathrm{P} = \frac{31\,420}{746} = 42.1\, \boldsymbol{hp}$$

Question 3 (1/2)

The air in a **10-cm-**diameter cylinder shown is heated until the spring is compressed **50 mm**. Find the work done by the air on the frictionless piston. The spring is initially unstretched, as shown.



The pressure in the cylinder is initially found from a force balance as shown on the free-body diagram:



$$P_1 A = P_{atm} A + W$$

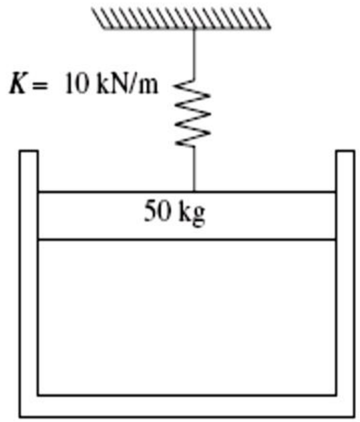
$$P_1 \pi \times 0.05^2$$

$$= 100\,000 \times \pi \times 0.05^2 + 50 \times 9.81$$

$$\therefore \boldsymbol{P_1} = 162\,500\ \textbf{Pa}$$

Question 3 (2/2)

The air in a **10-cm-**diameter cylinder shown is heated until the spring is compressed **50 mm**. Find the work done by the air on the frictionless piston. The spring is initially unstretched, as shown.



To raise the piston a distance of 50 mm, without the spring, the work required would be force times distance:

$$W = PA \times d$$
$$= 162\,500 \times (\pi \times 0.05^2) \times 0.05$$
$$= 63.81 \text{ J}$$

The work required to compress the spring is calculated as:

$$W = \frac{1}{2}K(x_2^2 - x_1^2) \quad = \frac{1}{2} \times 10\,000 \times 0.05^2 \quad = 12.5 \textbf{ J}$$

The total work is then found by summing the two values:

$$W_{total} = 63.81 + 12.5 = 76.31 \textbf{ J}$$

Question 4

Energy is added to a piston-cylinder arrangement, and the piston is withdrawn in such a way that the temperature remains constant. The initial pressure and volume are 200 kPa and 2 m^3, respectively. If the final pressure is 100 kPa, calculate the work done by the ideal gas on the piston.

Assuming the expnsion to be a quasi-equilibrium process, the work may be determined as:

$$W_{1-2} = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{C}{V} dV$$

But for an isothermal process:

$$\mathrm{PV = C}$$

We may therefore compute the constant ***C*** as:

$$\mathrm{C = P_1 V_1}$$
$$= 200 \times 2 = 400 \text{ kJ}$$

Also:

$$P_1 V_1 = P_2 V_2$$

$$V_2 = \frac{P_1 V_1}{P_2} = \frac{200 \times 2}{100} = 4 \text{ m}^3$$

$$W_{1-2} = \int_2^4 \frac{400}{V} dV = 400 \ln \frac{4}{2} = 277 \text{ kJ}$$