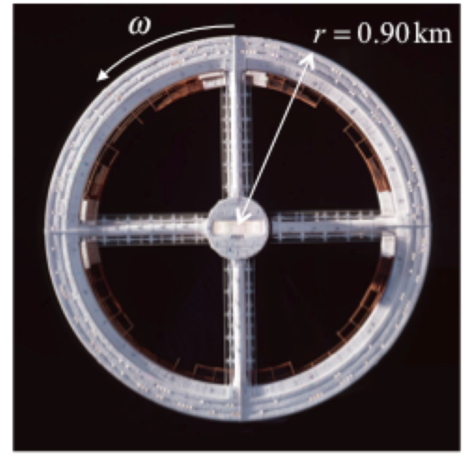
Midterm Exam 3

Exam 3
Approximate grades

4.0	3.5	3.0	2.5	2.0-0
16 – 13,	12 – 10,	9 – 6,	5 – 4,	< 4

Exam 3
Solutions

1. Astronauts experience "artificial gravity" on the inside of the circular wall of a space station consisting of a large tube rotating about the central axis as shown in the picture. If the tube has a radius, $r = 0.900$ km, at what angular speed ω must the station be rotating to create the artificial acceleration of 9.81 m/s^2?



$$a_c = \omega^2 r = g$$

$$\omega = \sqrt{g/r} = \sqrt{9.81/900}\ \text{rad/s} = 0.104\ \text{rad/s}$$

2. A compact disk player is turned on causing the disk to begin to rotate. It reaches a rotation speed of 43.9 rad/s in 3.35 s. Find the average acceleration of the disk.

$$\alpha = \frac{\omega - \omega_0}{t} = \frac{43.9}{3.35}\text{rad/s}^2 = 13.1\text{rad/s}^2$$

3. An object in uniform circular motion (constant speed v around a circle with constant R) is acted upon by a centripetal force. Which statement below is **FALSE**?

The centripetal force:

A) Is directed inward toward the center of the circle.
B) Changes direction continuously.
C) Depends on the mass of the object.
D) Decreases for circles with a larger radius.
E) Increases linearly with the speed around the circle.
F) Cannot affect the net force in the direction of motion.
G) Cannot affect the tangential speed.
H) Cannot affect the tangential acceleration.

$F_c = mv^2 / r$ depends on square of speed

4. A spinning circular saw rotates at 550 rpm as it starts to cut. The rotation has dropped to 450 rpm by the time it finished cutting. If the disk undergoes a constant angular acceleration of $-9.32 \times 10^{-2}\,\text{rad/s}^2$, find the angular displacement of the saw.

$$\omega = \left(\tfrac{2\pi}{60}\right) 450\,\text{rpm} = 47.12\,\text{rad/s}$$

$$\omega_0 = \left(\tfrac{2\pi}{60}\right) 550\,\text{rpm} = 57.60\,\text{rad/s}$$

$$\theta = \frac{\omega^2 - \omega_0^2}{2\alpha} = \frac{2220 - 3317}{2(-0.0932)}\,\text{rad} = 5.89 \times 10^3\,\text{rad}$$

5. A potter's wheel ($I_{Disk} = \frac{1}{2}MR^2$) of mass 7.00 kg and radius 0.650 m spins about its central axis. A 2.10 kg lump of clay is dropped onto the wheel at a distance 0.410 m from the axis. Calculate the final rotational inertia of the system.

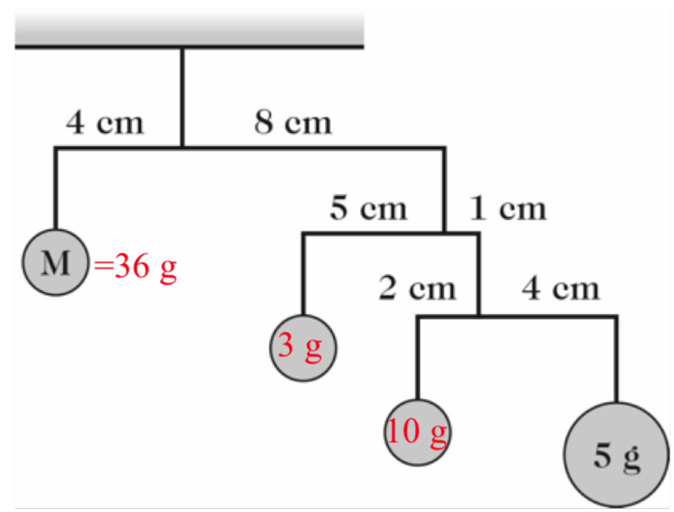
$$I_T = I_{Disk} + I_{Clay} = \tfrac{1}{2}MR^2 + mr^2$$
$$= [(0.5)(7.00)(0.650)^2 + (2.1)(0.41)^2]\,\mathrm{kg\cdot m^2}$$
$$= 1.83\,\mathrm{kg\cdot m^2}$$

6. A force of 16.88 N is applied tangentially to a wheel of radius 0.340 m and gives rise to an angular acceleration of 1.20 rad/s^2. Calculate the rotational inertia of the wheel.

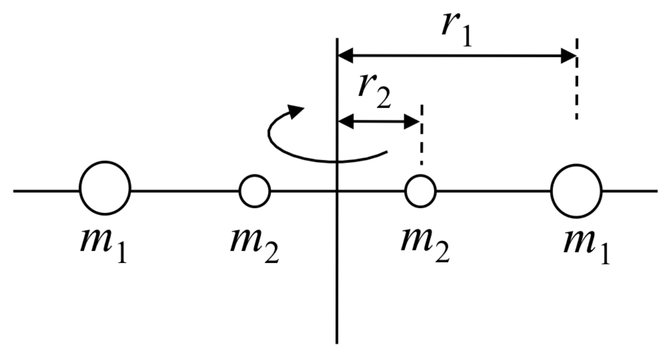
$$I = \tau/\alpha,\ \tau = FR$$
$$= FR/\alpha = [(16.88)(0.34)/1.2]\mathrm{rad/s^2}$$
$$= 4.78\,\mathrm{kg\cdot m^2}$$

7. What is the value of the mass M that will balance the mobile?

$$\sum \tau = 0 \text{ on every mobile arm,}$$
$$0 = -m_1 g r_1 + m_2 g r_2 \quad (m_1 \text{ on right, } m_2 \text{ on left})$$
$$\text{For each arm: } m_2 = (m_1)(r_1/r_2)$$
$$\text{lowest arm: } m_2 = (5\,\mathrm{g})(4/2) = 10\,\mathrm{g}, \text{ total mass} = (5+10)\mathrm{g} = 15\ \mathrm{g}$$
$$\text{middle arm: } m_2 = (15\,\mathrm{g})(1/5) = 3\,\mathrm{g}, \text{ total mass} = (15+3)\,\mathrm{g} = 18\,\mathrm{g}$$
$$\text{top arm}: \mathrm{M} = (18\,\mathrm{g})(8/4) = 36\,\mathrm{g}$$



8. On a rod of negligible mass, two spheres with mass m_1 = 0.50 kg are placed symmetrically at r_1 = 0.50 m, and two spheres with mass m_2 = 0.25 kg are placed symmetrically at r_2 = 0.20 m, from a rotation axis, as shown in the figure. The bar rotates with an angular velocity of 0.60 rad/s. If both inner masses move outward to r_2 = 0.40 m, what is the new angular velocity.



$$I_0 = \sum(mr^2)_i = 2m_1r_1^2 + 2m_2r_2^2$$
$$= 2(0.5)(0.5)^2\,\text{kg}\cdot\text{m}^2 + 2(0.25)(0.2)^2\,\text{kg}\cdot\text{m}^2$$
$$= \left(0.25 + 0.02\right)\text{kg}\cdot\text{m}^2 = 0.27\,\text{kg}\cdot\text{m}^2$$
$$I = 2(0.5)(0.5)^2\,\text{kg}\cdot\text{m}^2 + 2(0.25)(0.4)^2\,\text{kg}\cdot\text{m}^2$$
$$= \left(0.25 + 0.08\right)\text{kg}\cdot\text{m}^2 = 0.33\,\text{kg}\cdot\text{m}^2$$

Angular Momentum conservation: $I_0\omega_0 = I\omega$

$$\omega = \left(I_0 / I\right)\omega_0 = \left(0.27 / 0.33\right)0.60\,\text{rad} = 0.491\,\text{rad}$$

9. The gravitational force on a mass *m* on the surface of the earth is $F = GmM/R^2$, where *M* and *R* are the mass and radius of the earth. The mass and radius of the moon are 7.40×10^{22} kg and 1.70×10^6 m, respectively. What is the weight of a 1.0-kg object on the surface of the moon?

$(G = 6.67\times10^{-11}\ \text{Nm}^2/\text{kg}^2)$

$$F = \frac{GmM}{R^2} = \frac{(6.67\times10^{-11})(1.0)(7.40\times10^{22})}{\left(1.70\times10^6\right)^2}\,\text{N}$$
$$= 17.1\times10^{-1}\,\text{N} = 1.71\,\text{N}$$

10. Which one of the following statements best explains why an astronaut experiences "weightlessness" in an orbit 1237 km above the earth?

C) The spaceship is in free fall so its floor cannot press upward on the astronaut.

11. Young's modulus of nylon is 3.70×10^9 N/m^2. A force of 6.00×10^5 N is applied to a length of nylon 1.50-m long and it stretches 0.973 mm. What is the cross sectional area of the nylon?

$$\frac{F}{A} = Y\frac{\Delta L}{L}$$

$$A = \frac{FL}{Y\Delta L} = \frac{(6.0\times10^5)(1.5)}{(3.7\times10^9)(9.73\times10^{-4})}\,\text{m}^2$$

$$= 0.250\,\text{m}^2$$

12. Water flows horizontally through a pipe at a pressure of 2.05×10^5 Pa with a speed of 10.0 m/s. The pipe then rises 4m higher and again becomes horizontal. What is the pressure in the pipe at this new height?

Same pipe throughout, $v = \text{constant}$

Bernoulli's Eq.: $P_1 + \rho g h_1 = P_2 + \rho g h_2$

$$P_2 = P_1 + \rho g(h_1 - h_2) = 2.05\times10^5\,\text{Pa} + (10^3)(9.81)(-4)\,\text{Pa}$$

$$= (2.05 - 0.39)\times10^5\,\text{Pa} = 1.66\times10^5\,\text{Pa}$$

13. The specific heat of water is 4186 J/(kg-°C) and water's heat of fusion is 333 kJ/kg. An insulated container with 2.09 kg of water and 0.25 kg of ice at 0 °C is heated. How much heat must be added to the contents to melt the ice and leave only water at 10 °C?

$m_I = 0.25\,\text{kg}.$

After ice melts, $m_W = 0.25\,\text{kg} + 2.09\,\text{kg} = 2.34\,\text{kg}$

$$Q = m_I L_f + m_W c \Delta T$$

$$= 0.25(333\times10^3)\,\text{J} + (2.34)(4186)(10^\circ)$$

$$= 181\ \text{J}$$

14. A hollow cube, 10.0 cm on a side floats with half of its volume above pure water. What volume of lead (density 11,500 kg/m^3) must be added inside the cube to just make it sink?

Cube volume: $V_C = (0.1)^3 \text{m}^3$

To float $\frac{1}{2}$ under water:

$\rho_C V_C g = \rho_W V_W g = \rho_W (\frac{1}{2} V_C) g$ (displaced)

Therefore, $\rho_C = \frac{1}{2}\rho_W = 0.5(1000)\,\text{kg/m}^3 = 500\,\text{kg/m}^3$

To just sink cube:

$\rho_C V_C g + \rho_{Pb} V_{Pb} g = \rho_W V_C g$ (displaced)

$$V_{Pb} = \frac{(\rho_W - \rho_C)}{\rho_{Pb}} V_C = \frac{(1000-500)}{11.5\times 10^3}(10^{-3}\text{m}^3)$$

$= 43.5\times 10^{-6}\,\text{m}^3 = 43.5\,\text{cm}^3$

15. Helium atoms at 450.0 K have an RMS speed of 1675 m/s. If the temperature is increased to 600.0 K what is the new RMS speed of the helium atoms?

Starting Temperature T_0: $\frac{1}{2} m v_0^2 = \frac{3}{2} k_B T_0$

New Temperature T_1: $\frac{1}{2} m v_1^2 = \frac{3}{2} k_B T_1$

Divide Temp$_1$ by Temp$_0$: $\frac{v_1^2}{v_0^2} = \frac{T_1}{T_0}$ $\quad v_1 = v_0\sqrt{\frac{T_1}{T_0}} = (1675)\sqrt{\frac{600}{450}}\ \text{m/s} = 1934\ \text{m/s}$

16. Use the ideal gas law (molar gas constant $8.315\ \text{J}\cdot\text{mol}^{-1}\text{K}^{-1}$) to compute the density of helium gas at a temperature of 25°C and 1 atm. of pressure ($1.013\times 10^5\,\text{Pa}$). Note: a mole of Helium gas has a mass of $4.00\times 10^{-3}\text{kg}$

$PV = nRT \quad T(\text{Kelvin}) = (25° + 273) = 298\,\text{K}$

$$\frac{n}{V} = \frac{P}{RT} = \frac{1.013\times 10^5}{(8.315)(298)}\frac{\text{mol}}{\text{m}^3} = 40.88\frac{\text{mol}}{\text{m}^3}$$

$\rho = \left(4\times 10^{-3}\,\text{kg/mol}\right)\left(40.88\,\text{mol/m}^3\right) = 0.164\ \text{kg/m}^3$

Chapter 13

The Transfer of Heat

continued

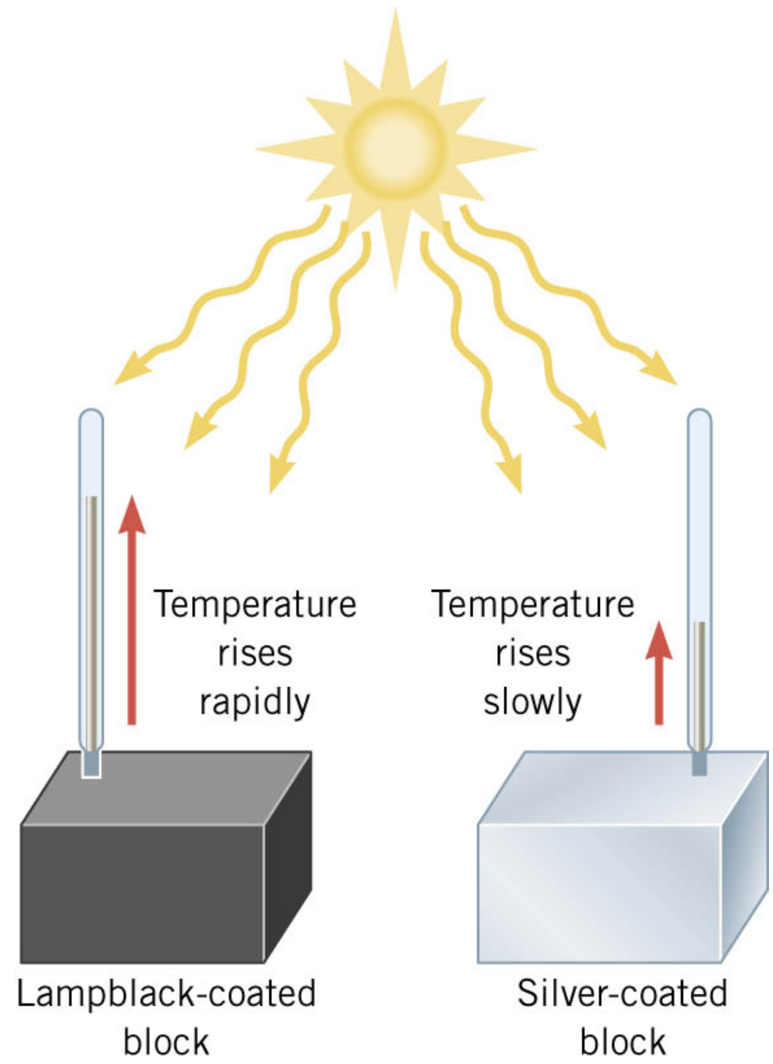
RADIATION

RADIATION

Radiation is the process in which energy is transferred by means of electromagnetic waves.

A material that is a good absorber is also a good emitter.

A material that absorbs completely is called a ***perfect blackbody***.



THE STEFAN-BOLTZMANN LAW OF RADIATION

The radiant energy *Q*, emitted in a time *t* by an object that has a Kelvin temperature *T*, a surface area *A*, and an emissivity *e*, is given by

$$Q = e\sigma T^4 At$$

emissivity $e =$ constant between 0 to 1

$e = 1$ (perfect black body emitter)

Stefan-Boltzmann constant

$\sigma = 5.67 \times 10^{-8}\ \mathrm{J/(s \cdot m^2 \cdot K^4)}$

Example A Supergiant Star

The supergiant star Betelgeuse has a surface temperature of about 2900 K and emits a power of approximately 4x10^{30} W. (W = J/s) Assuming Betelgeuse is a perfect emitter and spherical, find its radius.

power, $P = \dfrac{Q}{t}$

with $A = 4\pi r^2$ (surface area of sphere with radius r)

$$r = \sqrt{\frac{Q/t}{4\pi e\sigma T^4}} = \sqrt{\frac{4\times10^{30}\,\mathrm{W}}{4\pi(1)\left[5.67\times10^{-8}\,\mathrm{J/(s\cdot m^2\cdot K^4)}\right](2900\ \mathrm{K})^4}}$$

$$= 3\times10^{11}\,\mathrm{m}$$

Chapter 14

Thermodynamics

THE FIRST LAW OF THERMODYNAMICS

The internal energy of a system changes due to heat and work:

$$\Delta U = U_f - U_i = Q + W$$

$Q > 0$ system gains heat

$W > 0$ if work done on the system

The internal energy (U) of an Ideal Gas depends only on the temperature:

$$\text{Ideal Gas (only):} \quad U = \tfrac{3}{2} nRT \text{ or } U = \tfrac{3}{2} N k_B T$$

$$\Delta U = U_f - U_i = \tfrac{3}{2} nR(T_f - T_i)$$

Otherwise, values for both Q and W are needed to determine ΔU

Clicker Question 14.1

An insulated container is filled with a mixture of water and ice at zero °C. An electric heating element inside the container is used to add 1680 J of heat to the system while a paddle does 450 J of work by stirring. What is the increase in the internal energy of the ice-water system?

$$\Delta U = Q + W$$

a) 450 J

b) 1230 J

c) 1680 J

d) 2130 J

e) zero J

Clicker Question 14.1

An insulated container is filled with a mixture of water and ice at zero °C. An electric heating element inside the container is used to add 1680 J of heat to the system while a paddle does 450 J of work by stirring. What is the increase in the internal energy of the ice-water system?

$$\Delta U = Q + W$$

a) 450 J

b) 1230 J

c) 1680 J

d) 2130 J

e) zero J

$$\Delta U = Q + W; \quad W = 450\text{J}$$
$$= (1680 + 450)\ \text{J}$$
$$= 2130\ \text{J}$$

14.1 ***Thermal Processes***

Work done on a gas

$(\Delta P = 0)$ ***isobaric:*** constant pressure: $W = -P\Delta V$

$(\Delta V = 0)$ ***isochoric:*** constant volume: $W = -P\Delta V = 0$

For an Ideal Gas only

$(\Delta T = 0)$ ***isothermal:*** constant temperature: $W = nRT\ln\left(V_i / V_f\right)$

$(Q = 0)$ ***adiabatic:*** no transfer of heat: $W = \frac{3}{2} nR\left(T_f - T_i\right)$

14.2 Thermal Processes

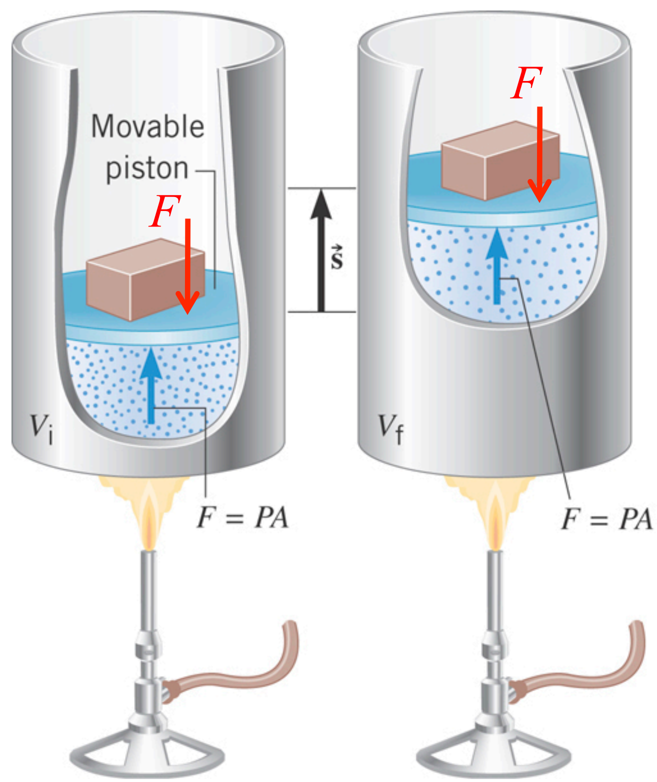
An ***isobaric*** process is one that occurs slowly at constant pressure.

$$\cos\theta = +1$$
$$\cos\theta = -1$$

If piston is pushed down by mass, $W_{\text{on gas}} > 0$.

If piston is pushed upward by pressure, $W_{\text{on gas}} < 0$

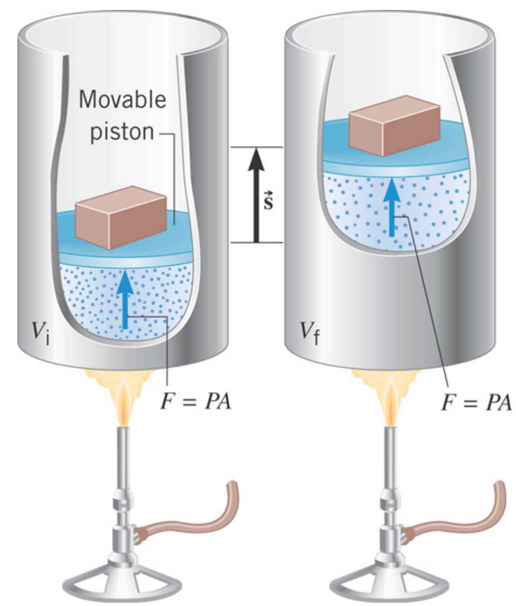
$$W = Fs\cos\theta = -P(As)$$
$$= -P\Delta V$$
$$= -P(V_f - V_i)$$



Example Isobaric Expansion of Water (Liquid)

One gram of water is placed in the cylinder and the pressure is maintained at 2.0×10^5 Pa. The temperature of the water is raised by 31°C. The water is in the liquid phase and expands by a very small amount, 1.0×10^{-8} m^3.

Find the work done and the change in internal energy.



$$W = -P\Delta V$$
$$= -\left(2.0\times10^5\,\text{Pa}\right)\left(1.0\times10^{-8}\,\text{m}^3\right) = -0.0020\,\text{J}$$

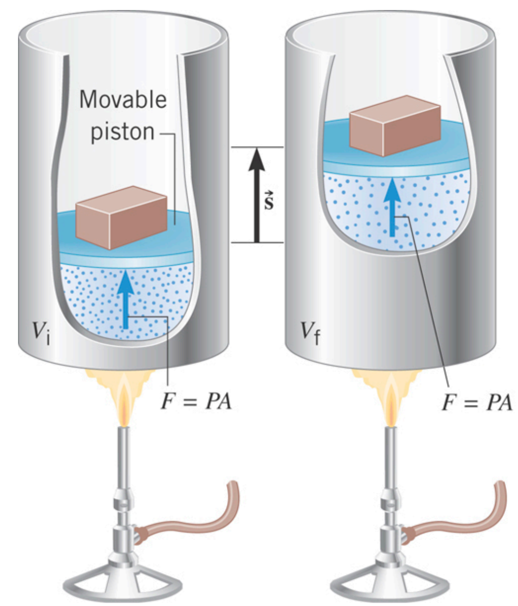
Liquid water $\Delta V \sim 0$

$$Q = mc\Delta T$$
$$c_{\text{water}} = 4186\,\text{J}/\left(\text{kg}\cdot\text{C}^\circ\right)$$
$$= \left(0.0010\text{ kg}\right)\left[4186\,\text{J}/\left(\text{kg}\cdot\text{C}^\circ\right)\right]\left(31\text{ C}^\circ\right) = 130\text{ J}$$

$$\Delta U = Q - W = 130\text{ J} - 0.0020\text{ J} = 130\text{ J}$$

Example Isobaric Expansion of Water (Vapor)

One gram of water vapor is placed in the cylinder and the pressure is maintained at 2.0×10^{5} Pa. The temperature of the vapor is raised by 31°C, and the gas expands by 7.1×10^{-5} m^3. Heat capacity of the gas is 2020 J/(kg-C°).



Find the work done and the change in internal energy.

$$W = -P\Delta V = -(2.0\times10^{5}\ \text{Pa})(7.1\times10^{-5}\text{m}^{3})$$
$$= -14.2\ \text{J}$$

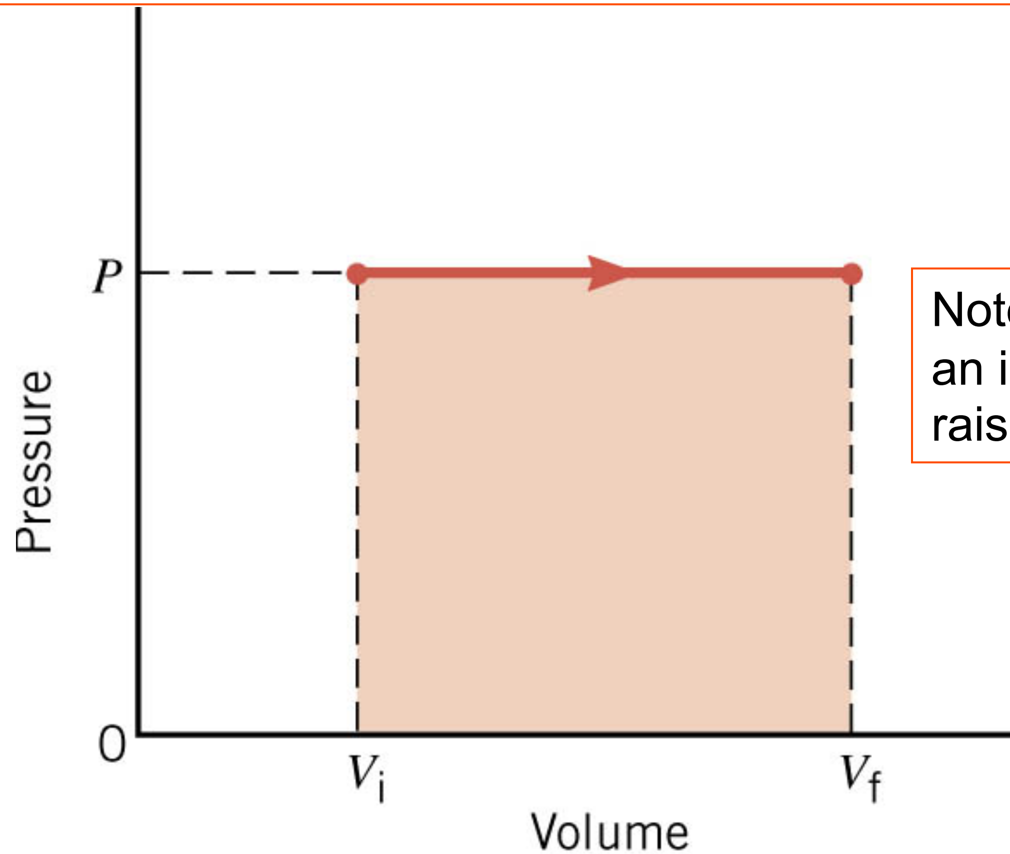
$$Q = mc\Delta T$$
$$= (0.0010\ \text{kg})\left[2020\,\text{J}/(\text{kg}\cdot\text{C}^{\circ})\right](31\ \text{C}^{\circ}) = 63\ \text{J}$$

$$\Delta U = Q + W = 63\text{J} + (-14\ \text{J}) = 49\ \text{J}$$

14.2 Thermal Processes

$$W = -P\Delta V = -P\left(V_f - V_i\right)$$

The work done on a gas at constant pressure - the work done is (minus) the area under a P-V diagram.



Note: the temperature of an ideal gas must be raised to do this.

Clicker Question 14.2

An ideal gas at a constant pressure of 1x10^5 Pa is reduced in volume from 1.00 m^3 to 0.25 m^3. What work was done on the gas?

$$W = -P\Delta V$$

a) zero J

b) 0.25×10^5 J

c) 0.50×10^5 J

d) 0.75×10^5 J

e) 4.00×10^5 J

Clicker Question 14.2

An ideal gas at a constant pressure of 1×10^5 Pa is reduced in volume from 1.00 m^3 to 0.25 m^3. What work was done on the gas?

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a) zero J

b) 0.25×10^5 J

c) 0.50×10^5 J

d) 0.75×10^5 J

e) 4.00×10^5 J

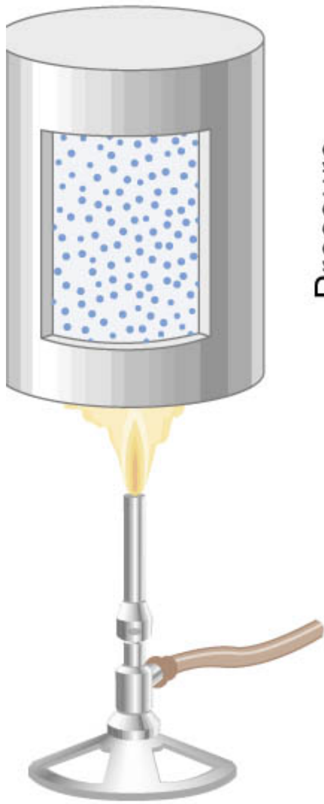
$$W = -P\Delta V = -P\left(V_f - V_i\right)$$

$$= -(1 \times 10^5 \text{ Pa})\ (0.25 - 1.00)\text{m}^3$$

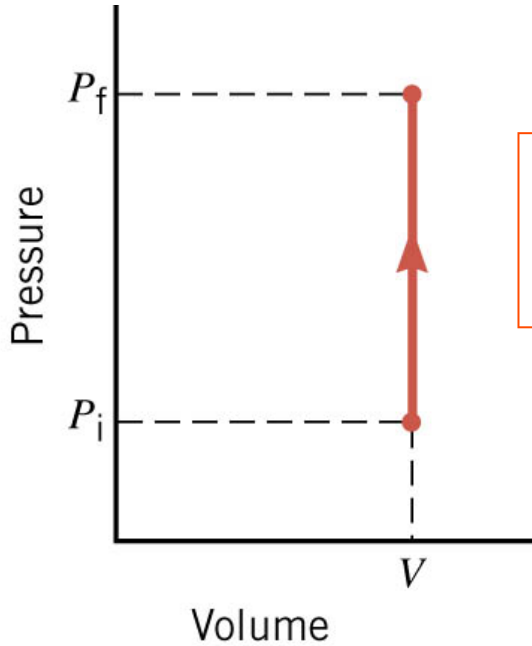
$$= 0.75 \times 10^5 \text{ J}$$

14.2 Thermal Processes

isochoric: constant volume



(a)



(b)

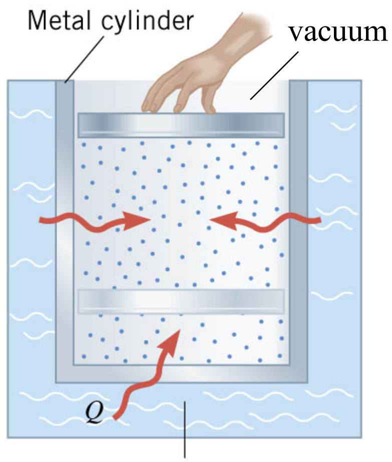
The work done at constant volume is the area under a P-V diagram. The area is zero!

$$W = 0$$

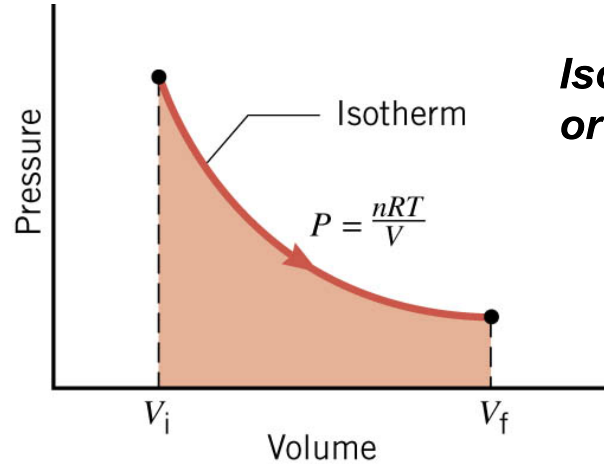
$$\Delta U = Q + W = Q$$

Change in internal energy is equal to the heat added.

ISOTHERMAL EXPANSION OR COMPRESSION



(a)



(b)

Isothermal expansion or compression of an ideal gas

$$W_{\text{on gas}} = nRT\ln\left(\frac{V_i}{V_f}\right)$$

Example 5 Isothermal Expansion of an Ideal Gas

Two moles of argon (ideal gas) expand isothermally at 298K, from initial volume of 0.025m^3 to a final volume of 0.050m^3. Find (a) the work done by the gas, (b) change in gas internal energy, and (c) the heat supplied.

a) $W_{\text{on gas}} = nRT\ln\left(V_i/V_f\right)$

$$= (2.0\text{ mol})\left(8.31\text{J}/(\text{mol}\cdot\text{K})\right)(298\text{ K})\ln\left(\frac{0.025}{0.050}\right)$$

$$= -3400\text{ J}$$

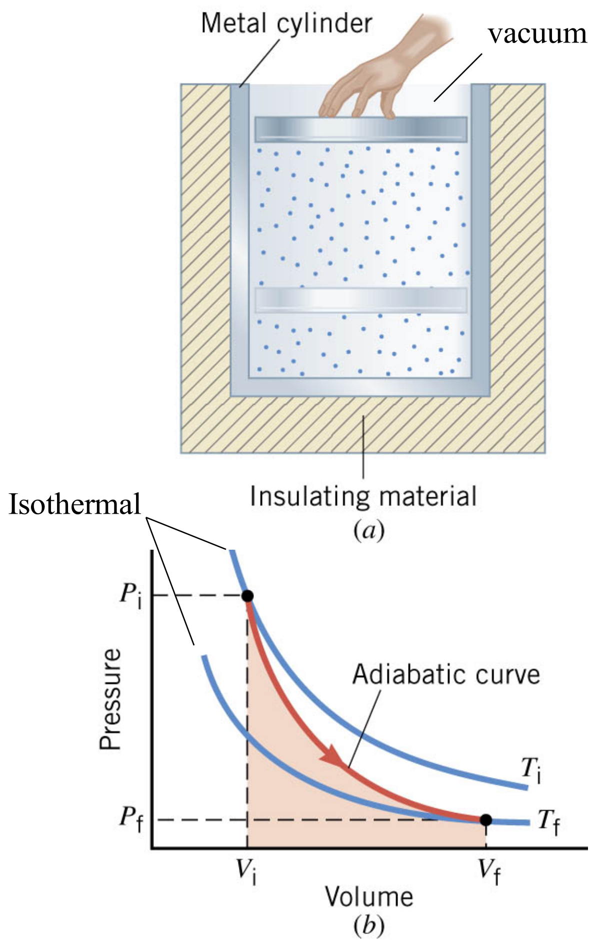
b) $\Delta U = U_f - U_i = \frac{3}{2}nR\Delta T$

$\Delta T = 0$ therefore $\Delta U = 0$

c) $\Delta U = Q + W = 0$

$Q = -W = 3400\text{J}$

14.2 Thermal Processes Using and Ideal Gas



ADIABATIC EXPANSION OR COMPRESSION

Adiabatic expansion or compression of a monatomic ideal gas

$$W_{\text{on gas}} = \tfrac{3}{2} nR\left(T_i - T_f\right)$$

Adiabatic expansion or compression of a monatomic ideal gas

$$P_i V_i^{\gamma} = P_f V_f^{\gamma}$$

$$\gamma = c_P / c_V$$

Ratio of heat capacity at constant P over heat capacity at constant V.

These are needed to understand basic operation of refrigerators and engines

ADIABATIC EXPANSION OR COMPRESSION

ISOTHERMAL EXPANSION OR COMPRESSION

14.2 Specific Heat Capacities

To relate heat and temperature change in solids and liquids (mass in kg), use:

$$Q = mc\Delta T \qquad \text{specific heat capacity, } c \ \left[\mathrm{J}/\left(\mathrm{kg}\cdot{}^\circ\mathrm{C}\right)\right]$$

For gases, the amount of gas is given in moles, use molar heat capacities:

$$Q = nC\Delta T \qquad \text{molar heat capacity, } C \ \left[\mathrm{J}/\left(\mathrm{mole}\cdot{}^\circ\mathrm{C}\right)\right]$$

$$C = \left(m/n\right)c = m_u c; \quad m_u = \text{mass/mole (kg)}$$

ALSO, for gases it is necessary to distinguish between the molar specific heat capacities at constant pressure and at constant volume:

$$C_P, C_V$$

14.2 Specific Heat Capacities

$$\text{Ideal Gas: } PV = nRT; \quad \Delta U = \tfrac{3}{2} nR\Delta T$$

$$\text{1st Law of Thermodynamics: } \Delta U = Q + W_{\text{on gas}}$$

Constant Pressure ($\Delta P = 0$)

$$W_P = -P\Delta V = -nR\Delta T$$

$$Q_P = \Delta U - W = \tfrac{3}{2} nR\Delta T + nR\Delta T = \tfrac{5}{2} nR\Delta T$$

Constant pressure for a monatomic ideal gas

$$Q_P = nC_P\Delta T$$

$$C_P = \tfrac{5}{2} R$$

Constant Volume ($\Delta V = 0$)

$$W_V = -P\Delta V = 0$$

$$Q_V = \Delta U - W = \tfrac{3}{2} nR\Delta T = \tfrac{3}{2} nR\Delta T$$

Constant volume for a monatomic ideal gas

$$Q_V = nC_V\Delta T$$

$$C_V = \tfrac{3}{2} R$$

monatomic ideal gas

$$\gamma = C_P / C_V = \tfrac{5}{2} R / \tfrac{3}{2} R = 5/3$$

any ideal gas

$$C_P - C_V = R$$

14.3 The Second Law of Thermodynamics

The second law is a statement about the natural tendency of heat to flow from hot to cold, whereas the first law deals with energy conservation and focuses on both heat and work.

THE SECOND LAW OF THERMODYNAMICS: THE HEAT FLOW STATEMENT

Heat flows spontaneously from a substance at a higher temperature to a substance at a lower temperature and does not flow spontaneously in the reverse direction.

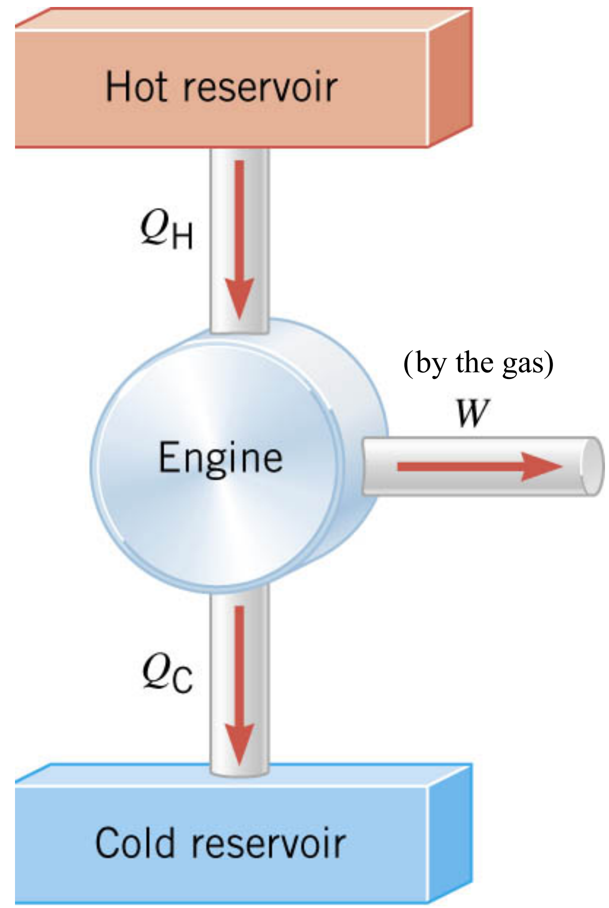
14.3 Heat Engines

A ***heat engine*** is any device that uses heat to perform work. It has three essential features.

1. Heat is supplied to the engine at a relatively high temperature from a place called the *hot reservoir.*

2. Part of the input heat is used to perform work by the *working substance* of the engine.

3. The remainder of the input heat is rejected to a place called the *cold reservoir.*



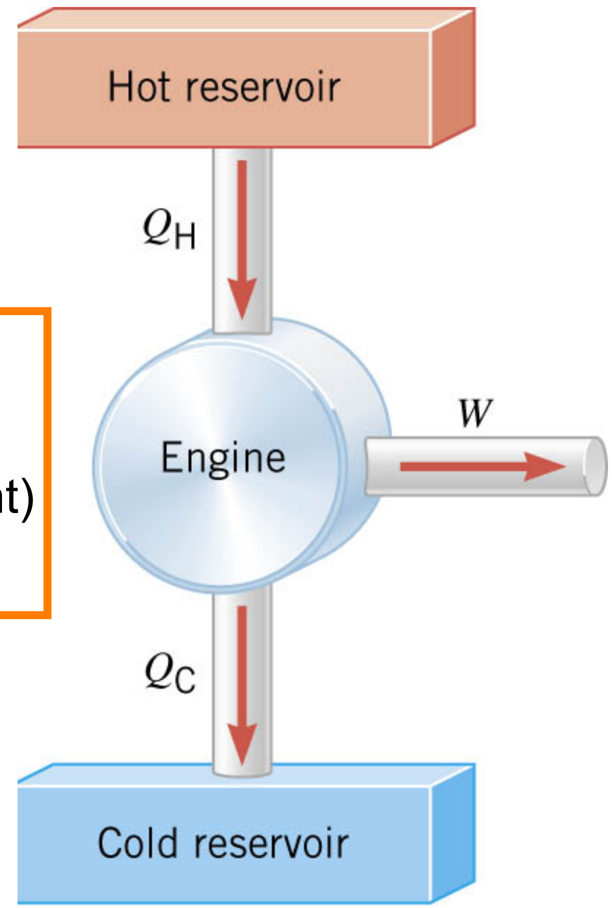
$$\left|Q_H\right| = \text{magnitude of input heat}$$

$$\left|Q_C\right| = \text{magnitude of rejected heat}$$

$$\left|W\right| = \text{magnitude of the work done}$$

Carnot Engine Working with an Ideal Gas

1. ISOTHERMAL EXPANSION ($Q_{in}=Q_H$, T_{Hot} constant)
2. ADIABATIC EXPANSION ($Q=0$, T drops to T_{Cold})
3. ISOTHERMAL COMPRESSION ($Q_{out}=Q_C$, T_{Cold} constant)
4. ADIABATIC COMPRESSION ($Q=0$, T rises to T_{Hot})



$$|Q_H| = \text{magnitude of input heat}$$

$$|Q_C| = \text{magnitude of rejected heat}$$

$$|W| = \text{magnitude of the work done}$$

14.3 ***Heat Engines***

The ***efficiency*** of a heat engine is defined as the ratio of the work done to the input heat:

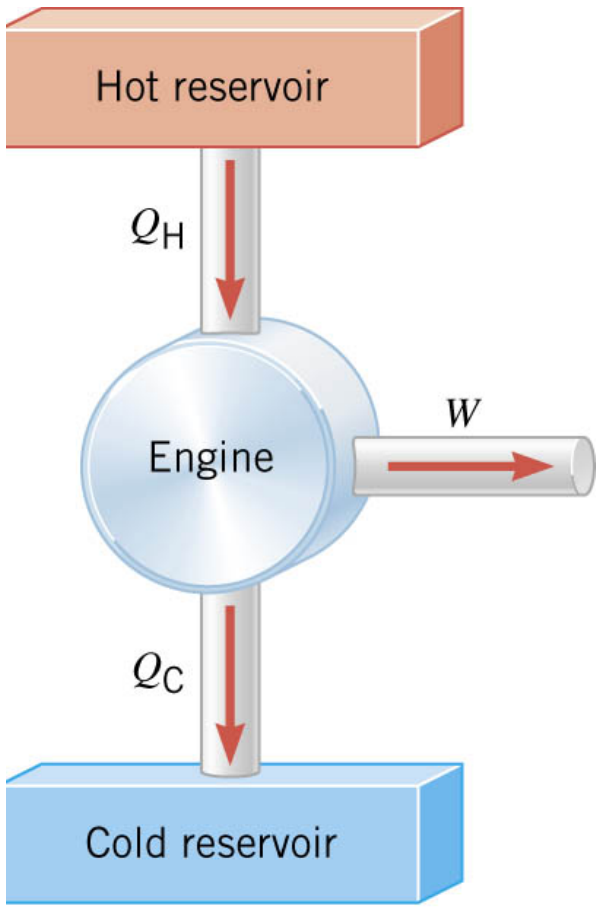
$$e = \frac{|W|}{|Q_H|}$$

If there are no other losses, then

$$|Q_H| = |W| + |Q_C|$$

$$\Downarrow$$

$$e = 1 - \frac{|Q_C|}{|Q_H|}$$



Example An Automobile Engine

An automobile engine has an efficiency of 22.0% and produces 2510 J of work. How much heat is rejected by the engine?

$$e = \frac{\left|W\right|}{\left|Q_H\right|}$$

$$= \frac{\left|W\right|}{\left|Q_C\right| + \left|W\right|} \quad \Rightarrow \quad e\left(\left|Q_C\right| + \left|W\right|\right) = \left|W\right|$$

$$\left|Q_C\right| = \frac{\left|W\right| - e\left|W\right|}{e} = \left|W\right|\left(\frac{1}{e} - 1\right) = 2510\,\mathrm{J}\left(\frac{1}{0.22} - 1\right)$$

$$= 8900\ \mathrm{J}$$

14.3 *Carnot's Principle and the Carnot Engine*

A reversible process is one in which both the system and the environment can be returned to exactly the states they were in before the process occurred.

CARNOT'S PRINCIPLE: AN ALTERNATIVE STATEMENT OF THE SECOND LAW OF THERMODYNAMICS

No irreversible engine operating between two reservoirs at constant temperatures can have a greater efficiency than a reversible engine operating between the same temperatures. Furthermore, all reversible engines operating between the same temperatures have the same efficiency.

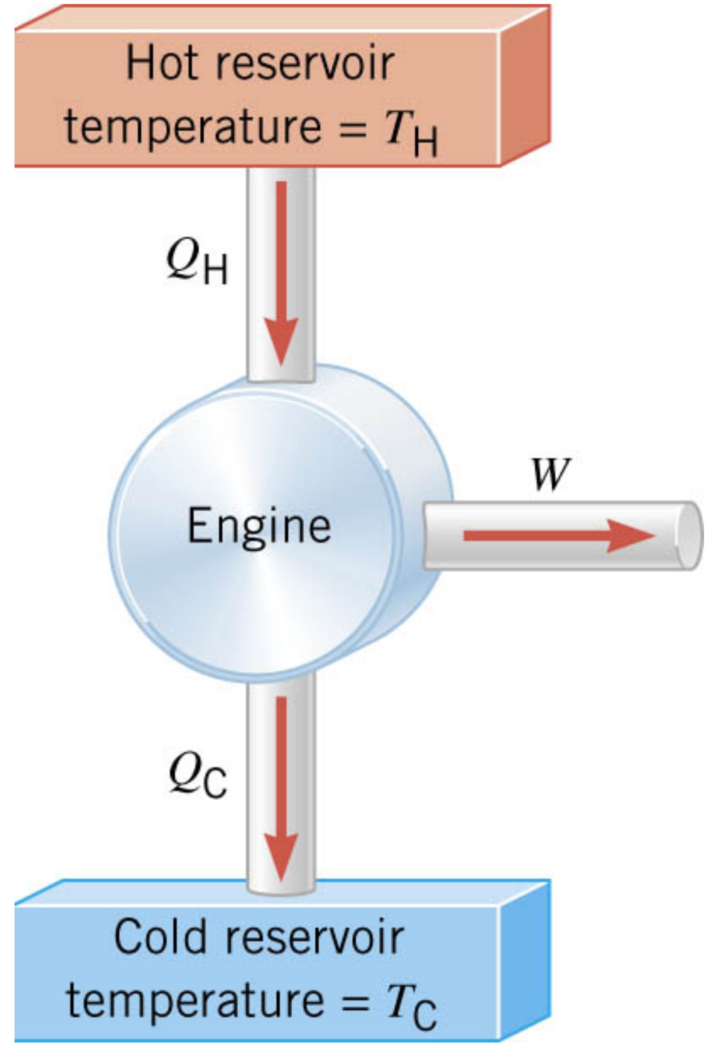
14.3 Carnot's Principle and the Carnot Engine

The ***Carnot engine*** is useful as an idealized model.

All of the heat input originates from a single temperature, and all the rejected heat goes into a cold reservoir at a single temperature.

Since the efficiency can only depend on the reservoir temperatures, the ratio of heats can only depend on those temperatures.

$$e = 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$



Example **A Tropical Ocean as a Heat Engine**

Surface temperature is 298.2 K, whereas 700 meters deep, the temperature is 280.2 K. Find the maximum efficiency for an engine operating between these two temperatures.

$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} = 1 - \frac{280.2\text{ K}}{298.2\text{ K}} = 0.060$$

Maximum of only 6% efficiency.
Real life will be worse.

Conceptual Example **Natural Limits on the Efficiency of a Heat Engine**

Consider a hypothetical engine that receives 1000 J of heat as input from a hot reservoir and delivers 1000J of work, rejecting no heat to a cold reservoir whose temperature is above 0 K. Decide whether this engine violates the first or second law of thermodynamics.

If $T_H > T_C > 0$

$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} \text{ must be less than 1}$$

$$e_{hypothetical} = \frac{|W|}{|Q_H|} = \frac{1000\,\text{J}}{1000\,\text{J}} = 1$$

Violates 2nd law of thermodynamics

14.3 Entropy

In general, irreversible processes cause us to lose some, but not necessarily all, of the ability to do work. This partial loss can be expressed in terms of a concept called ***entropy***.

Carnot engine

$$\frac{|Q_C|}{|Q_H|} = \frac{T_C}{T_H} \quad \Longrightarrow \quad \frac{|Q_C|}{T_C} = \frac{|Q_H|}{T_H}$$

entropy change

$$\Delta S = \left(\frac{Q}{T}\right)_R$$

R: reversible

14.3 Entropy

Entropy, like internal energy, is a function of the state of the system.

$$\Delta S = \left(\frac{Q}{T}\right)_R$$

Consider the entropy change of a Carnot engine. The entropy of the hot reservoir decreases and the entropy of the cold reservoir increases.

$$\Delta S = +\frac{|Q_C|}{T_C} - \frac{|Q_H|}{T_H} = 0$$

Reversible processes do not alter the entropy of the universe.