Summary Lecture 1 (glossery: see App. B, SG)

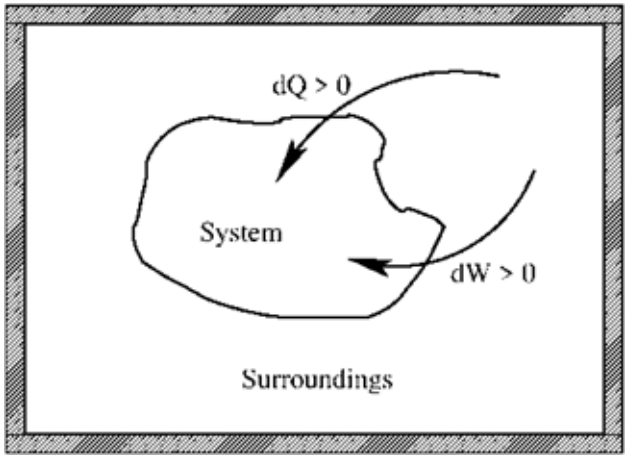
- **First law: conservation of energy**

$$dU = dW + dQ$$

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

$$\oint dU = 0$$

U is a state function



Reversible process

- Mechanical work

$$W = -\int P_{\text{ext}}\, dV \overset{=}{} -\int P dV$$

- Perfect gas

$$PV = nRT$$ Equation of state

- Perfect atomic gas

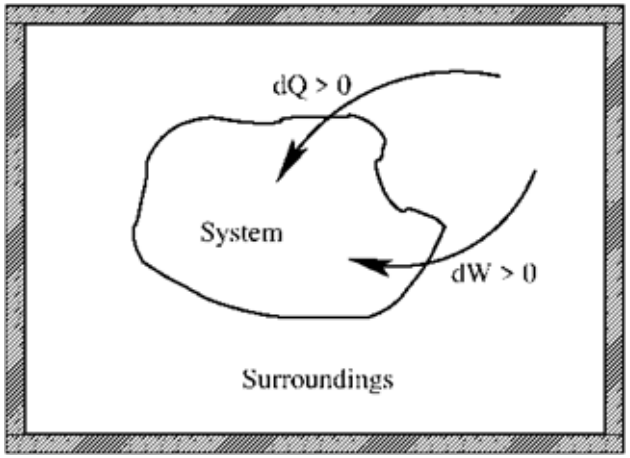
$$U = \frac{3}{2} nRT = \frac{3}{2} PV$$

Summary Lecture 2 (second law and entropy)

Second law:
for any spontaneous process

$$dS_{tot} = dS + dS_{sur} \geq 0$$

$$dS \equiv \frac{dQ^{rev}}{T}$$



S is a state function, so independent of path

Alternative form: Clausius inequality:

$$dQ \leq TdS$$

$$dQ^{rev} = TdS$$ **Reversible process**

$$dQ^{irr} < TdS$$ **Irreversible process**

Summary Lecture 2 (alternative energy functions)

Internal energy U

Enthalpy $H \equiv U + PV$

Helmholtz free energy $A \equiv U - TS$

Gibbs free energy $G \equiv H - TS$

State functions

$$dU = TdS - PdV \Rightarrow dU\big|_V = TdS$$

$$dH = TdS + VdP \Rightarrow dH\big|_P = TdS$$

$$dA = -SdT - PdV \Rightarrow dA\big|_{T,V} = 0$$

$$dG = -SdT + VdP \Rightarrow dG\big|_{T,P} = 0$$

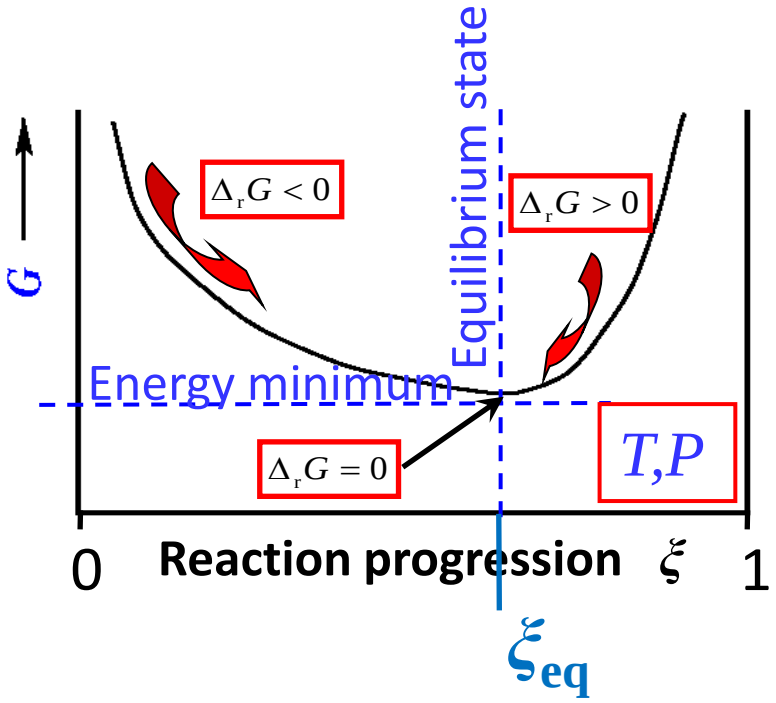
Heat capacities

$$C_V \equiv \left(\frac{\partial U}{\partial T}\right)\Big|_V \qquad C_P \equiv \left(\frac{\partial H}{\partial T}\right)\Big|_P$$

Summary Lecture 3 (chemical equilibria)

Second law→ $dG\big|_{P,T} \leq 0$

$$\Delta_r G \equiv \left(\frac{\partial G}{\partial \xi}\right)_{P,T}$$



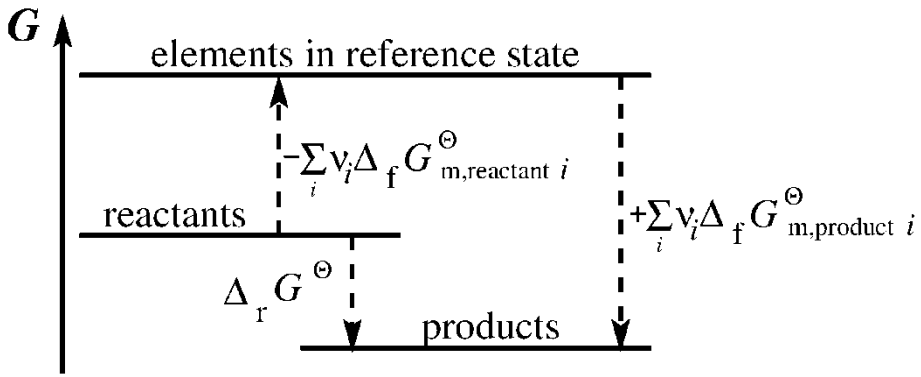
$$\Delta_r G = \Delta_r G^{\Theta} + RT \ln Q$$

$\Delta_r G$	reaction
$\Delta_r G < 0$	→
$\Delta_r G > 0$	←
$\Delta_r G = 0$	⇄

$$\Delta_r G^{\Theta} = \sum_i \nu_i \Delta_f G^{\Theta}_{m,i}$$

$$K = \exp\left[-\frac{\Delta_r G^{\Theta}}{RT}\right]$$

Summary Lecture 3 (formation energies)



$$\Delta_f G^{\Theta}_{m,i} = \Delta_f H^{\Theta}_{m,i} - T\Delta_f S^{\Theta}_{m,i}$$

At constant, chosen T

For all ellements in their reference states at T $\Delta_f G^{\Theta}_{m,i} \equiv 0$

For all ellements in their reference states at T $\Delta_f H^{\Theta}_{m,i} \equiv 0$

For gaseous mixtures

Partial pressure

$$P_i \equiv x_i P$$

Mole fraction

$$x_i \equiv \frac{n_i}{n} = \frac{n_i}{\sum_j n_j}$$

For perfect gas mixtures

$$Q = \prod_i \left(\frac{P_i}{P^{\Theta}} \right)^{\nu_i}$$

Summary Lecture 4 (activity)

For general systems:

$$\mu_i \equiv \mu_i^{\Theta} + RT \ln a_i$$

$$\Delta_r G = \Delta_r G^{\Theta} + RT \ln Q$$

$$Q = \prod_i a_i^{\nu_i}$$

$$\Delta_r G^{\Theta} = \sum_i \nu_i \Delta_f G^{\Theta}_{m,i}$$

$$\Delta_r G^{\Theta} = \sum_i \nu_i \mu_i^{\Theta}$$

$P^{\Theta} \equiv 1\,\text{bar};\ a_i^{\Theta} = 1;\ i^{\Theta}$ is pure

$$a_i = \frac{P_i}{P^{\Theta}}$$ **For perfect gas mixtures**

$$a_l \approx 1$$ **For pure liquids**

$$a_s \approx 1$$ **For pure solids**

$$a_i = \gamma_i^{(c)} \frac{c_i}{c^{\Theta}}$$ **with** $c^{\Theta} \equiv 1\,\text{mol/L}$

$$a_i = \gamma_i^{(b)} \frac{b_i}{b^{\Theta}}$$ **with** $b^{\Theta} \equiv 1\,\text{mol/kg}$

$$a_i = \gamma_i^{(x)} x_i$$

$$\text{pH} \equiv -\log a_{H^+}$$

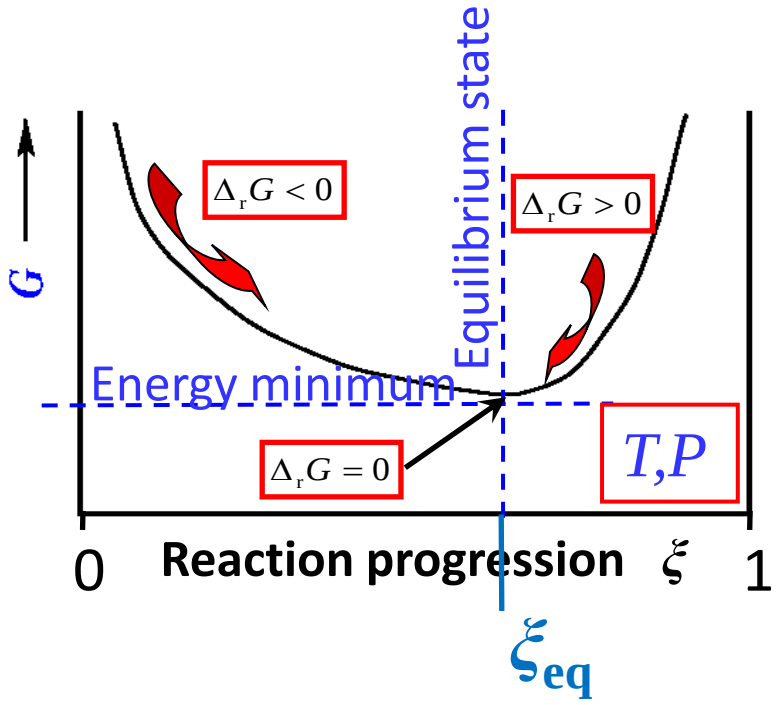
Summary Lecture 4 (electrochemistry)

$$\Delta_r G = \Delta_r G^{\Theta} + RT \ln Q$$

$$\Delta_r G = -\nu F E$$

$$E = E^{\Theta} - \frac{RT}{\nu F} \ln Q$$

Nernst equation

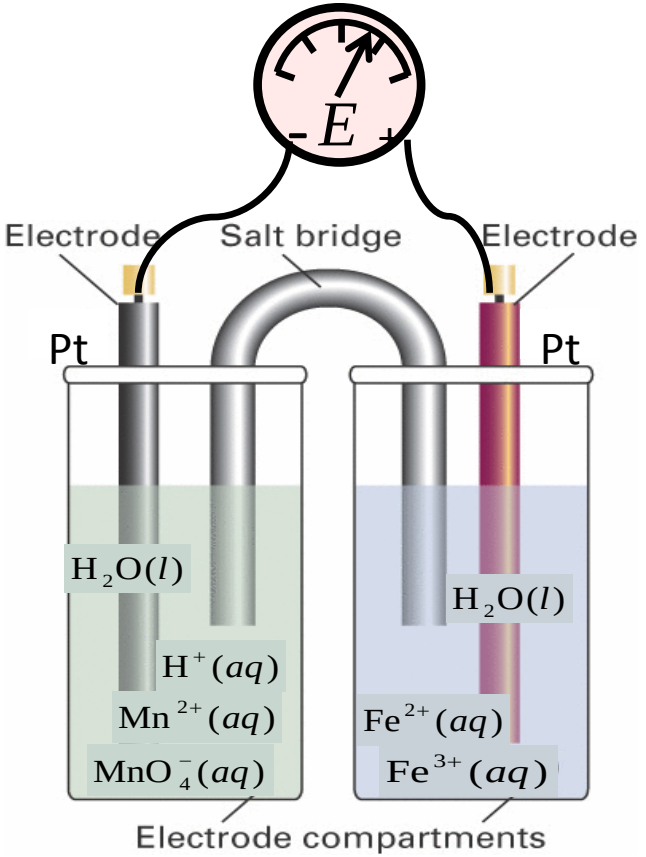


reaction

$\Delta_r G < 0$ $E > 0$ →

$\Delta_r G > 0$ $E < 0$ ←

$\Delta_r G = 0$ $E = 0$ ⟷



Summary Lecture 4 (electrochemistry)

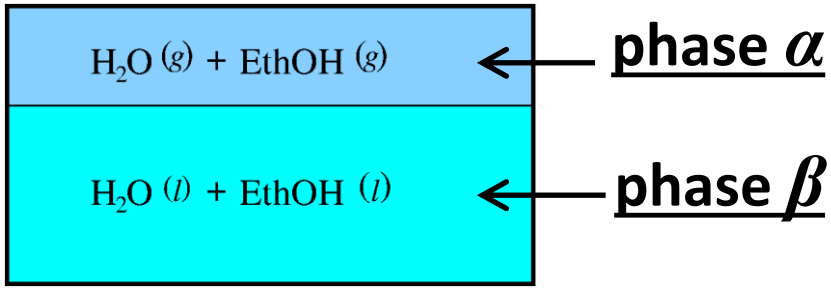
$$\Delta_f G^{\Theta}_{H^+(aq)} = \Delta_f H^{\Theta}_{H^+(aq)} \equiv 0 \text{ for all } T$$

$$E^{\Theta}_{2H^+/H_2} \equiv 0 \text{ for all } T$$

$$pH \equiv -^{10}\log a_{H^+} \approx -^{10}\log \left[H^+\right]$$

Summary Lecture 5: solutions or mixtures

Equilibrium between phases of component *i* in mixtures



in equilibrium: $\mu_{i,\alpha} = \mu_{i,\beta}$

$$G\big|_{P,T} = \sum_i \mu_i n_i$$

Real phase mixing $\Delta_{\text{mix}} G^{g,l} = nRT\left(x_{\text{A},g,l} \ln a_{\text{A},g,l} + x_{\text{B},g,l} \ln a_{\text{B},g,l}\right)$

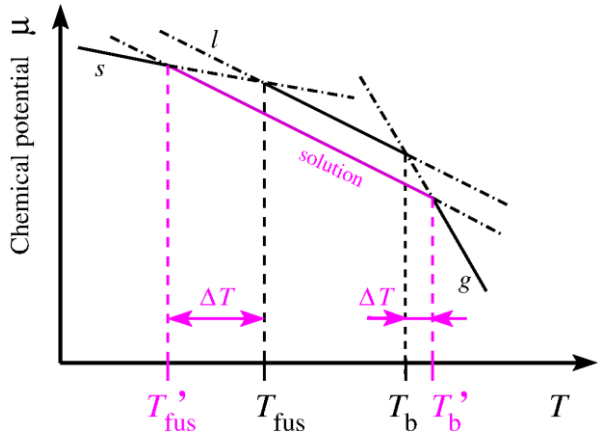
Perfect gas mixing $\Delta_{\text{mix}} G^{g,l} = nRT\left(x_{\text{A},g,l} \ln x_{\text{A},g,l} + x_{\text{B},g,l} \ln x_{\text{B},g,l}\right)$

Ideal solution (Raoult)

$\Delta_{\text{mix}} S = -nR\left(x_{\text{A}} \ln x_{\text{A}} + x_{\text{B}} \ln x_{\text{B}}\right)$

$\Delta_{\text{mix}} H = 0$

Summary Lecture 5: colligative properties



Freezing point depression

Boiling point elevation

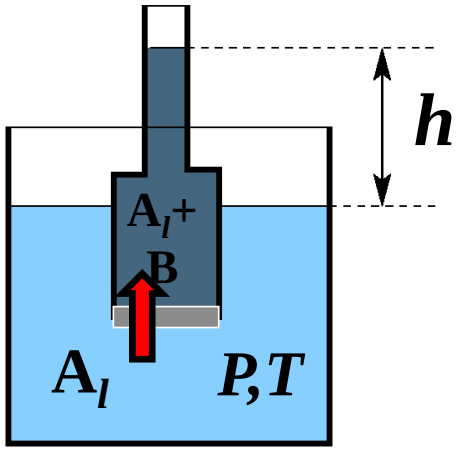
$$\Delta T \approx -\frac{RT^{*2}_{\mathrm{A,fus}}}{\Delta_{\mathrm{fus}} H^{*}_{\mathrm{m,A}}} \ln a_{\mathrm{A}}$$

$$\Delta T \approx -\frac{RT^{*2}_{\mathrm{A,vap}}}{\Delta_{\mathrm{vap}} H^{*}_{\mathrm{m,A}}} \ln a_{\mathrm{A}}$$

Ideal solution:

$$\Delta T \approx \frac{RT^{*2}_{\mathrm{A,fus}}}{\Delta_{\mathrm{fus}} H^{*}_{\mathrm{m,A}}} x_{\mathrm{B}}$$

$$\Delta T \approx \frac{RT^{*2}_{\mathrm{A,vap}}}{\Delta_{\mathrm{vap}} H^{*}_{\mathrm{m,A}}} x_{\mathrm{B}}$$



Osmosis

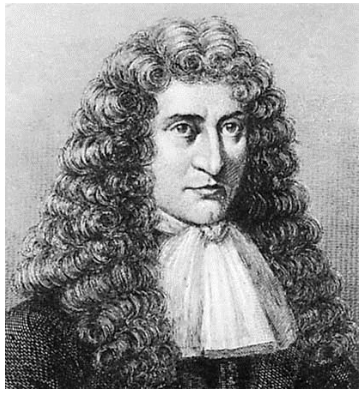
$$\rho g h = \Pi = -\frac{RT}{V^{*}_{\mathrm{A,m}}} \ln a_{\mathrm{A}}$$

Ideal solution:

$$\rho g h = \Pi \approx RT[\mathrm{B}]$$

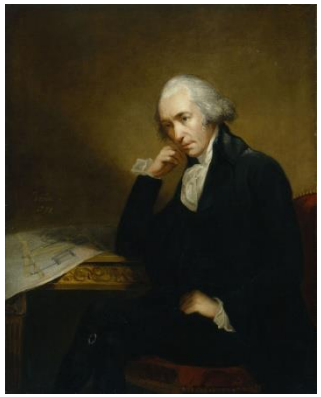
Lecture 6: Efficiency of processes

Lecture 6: Efficiency of processes: History



1690/1698

Heat → Work

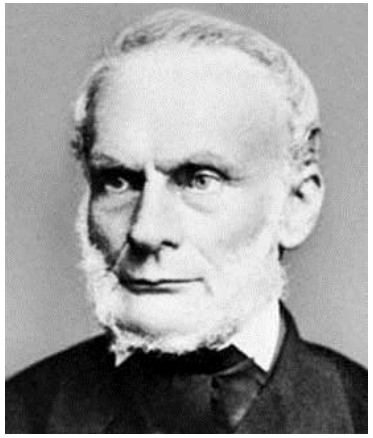


1784

Steam engine

1803/1824

Theory of efficiency



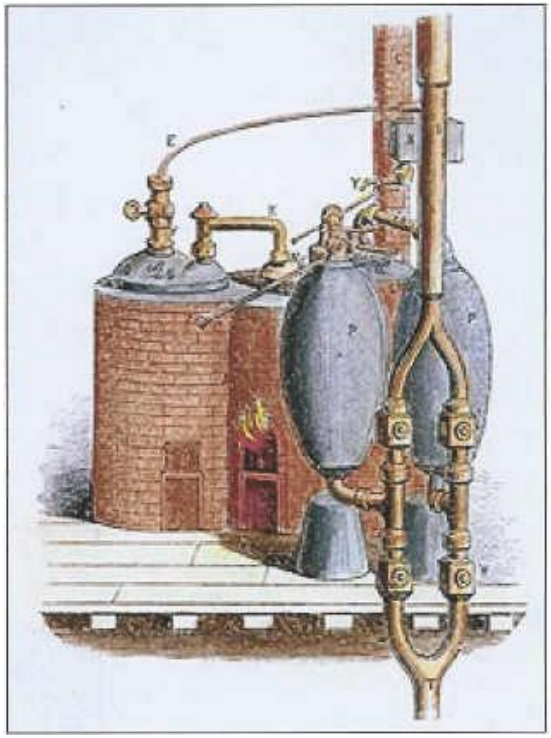
1854/1862

Definition Entropy

Lecture 6: History: Convert heat to work

Thomas Savery
1650-1715

vacuum
Steam-Water
pump

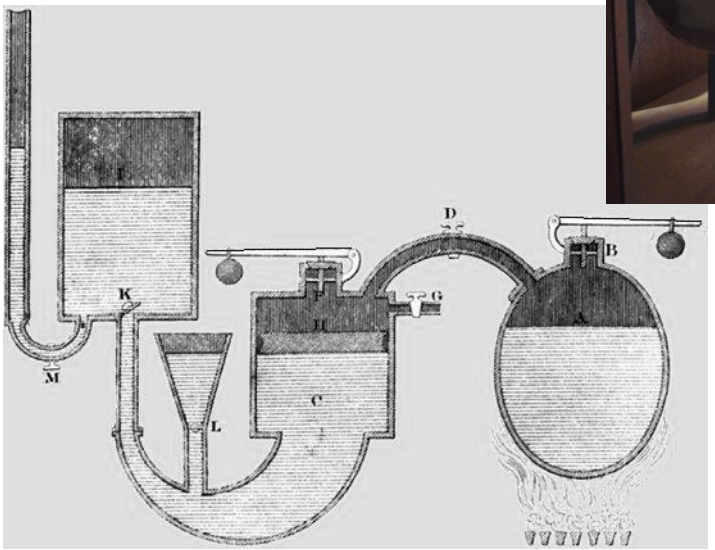


1698

Lecture 6: History: Convert heat to work

Denis Papin
1647-1712

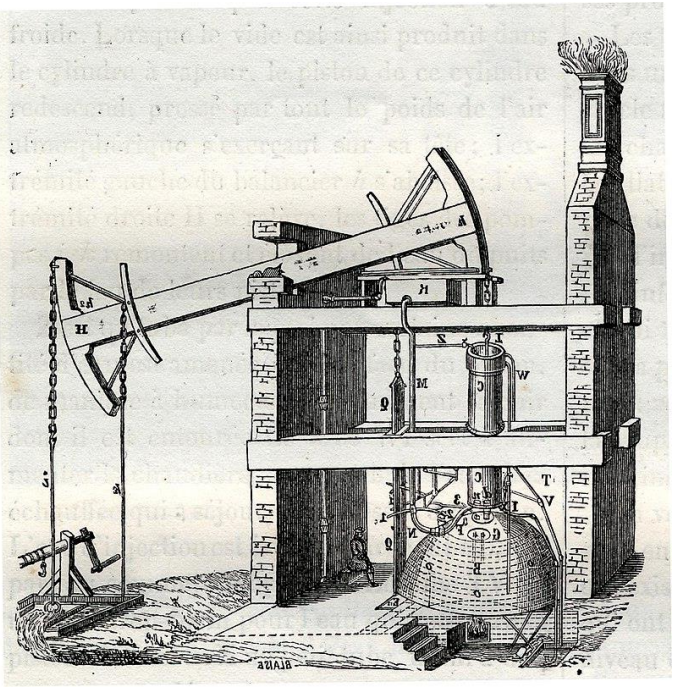
Steam-Water pump
Using a Piston



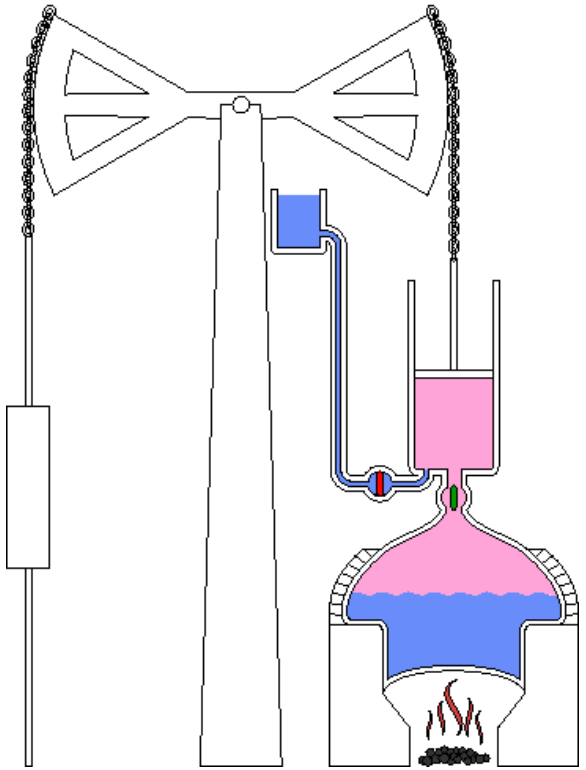
1690

Lecture 6: History: Convert heat to work

The Proprietors of the Invention for Raising Water by Fire

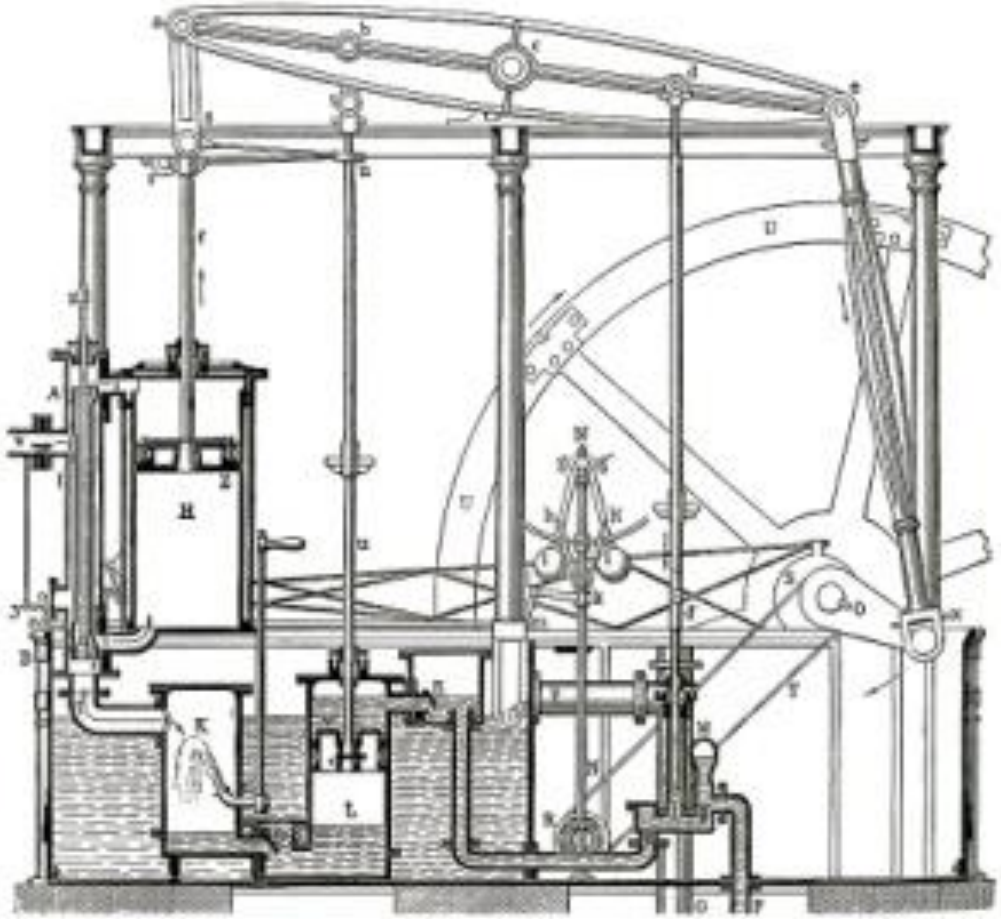


Thomas Newcomen
1664-1729
+
(Thomas Savery)

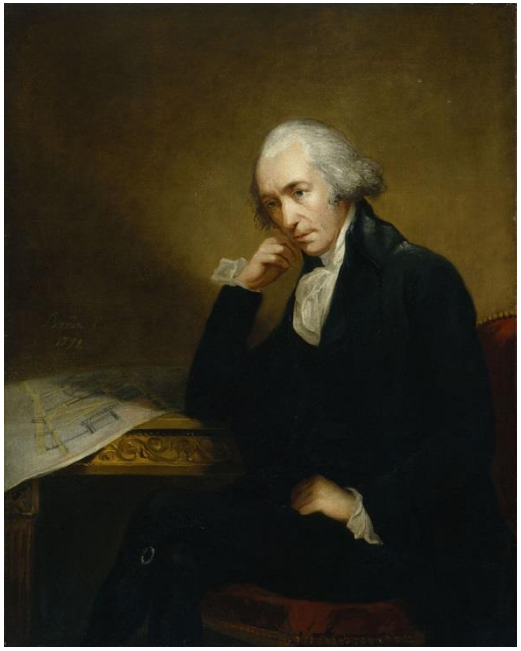


Efficiency: 2-5 %

Lecture 6: History: Convert heat to work



1784



James Watt
1736-1819

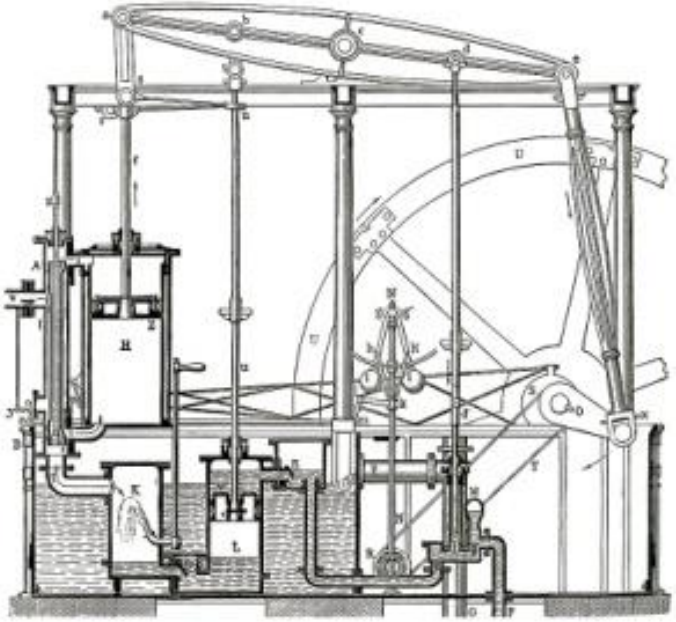
Steam engine efficiency: 25 %

Lecture 6: Steam engines: Convert heat to work

→ **Is the amount of (useful) work limited?**
→ **Is there an alternative medium for steam?**

Sadi Carnot
1796-1832

Thermodynamical model system: heat engine



Lecture 6: Steam engines: Convert heat to work

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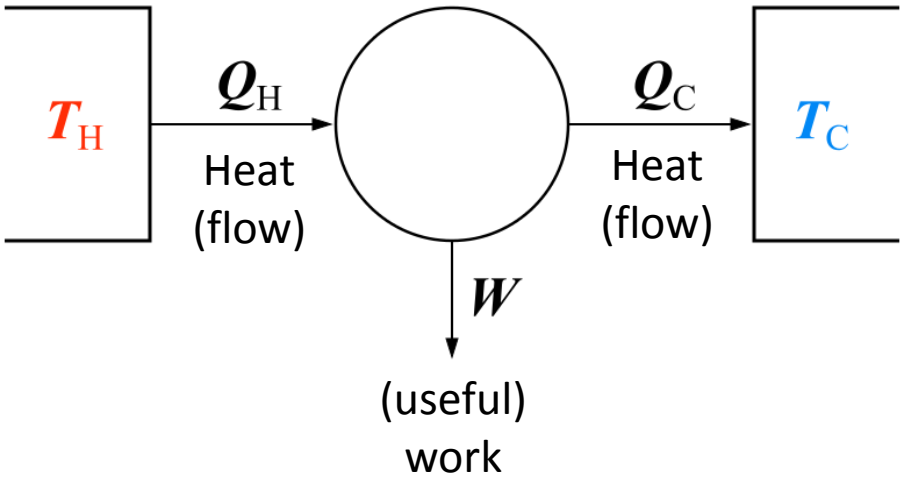
1796-1832

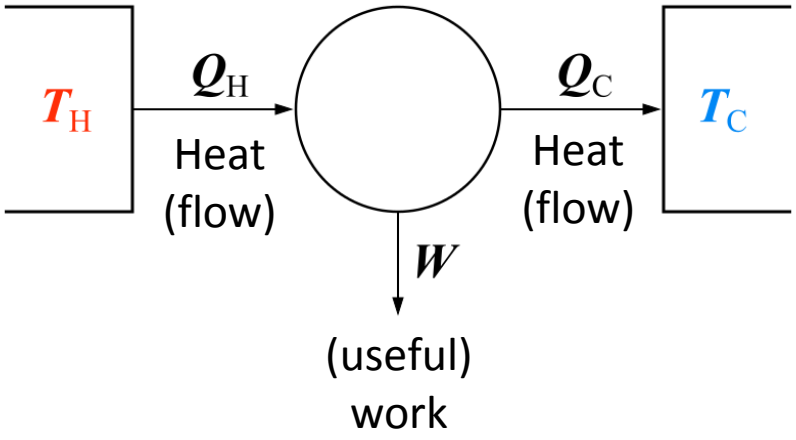
Thermodynamical model system: heat engine

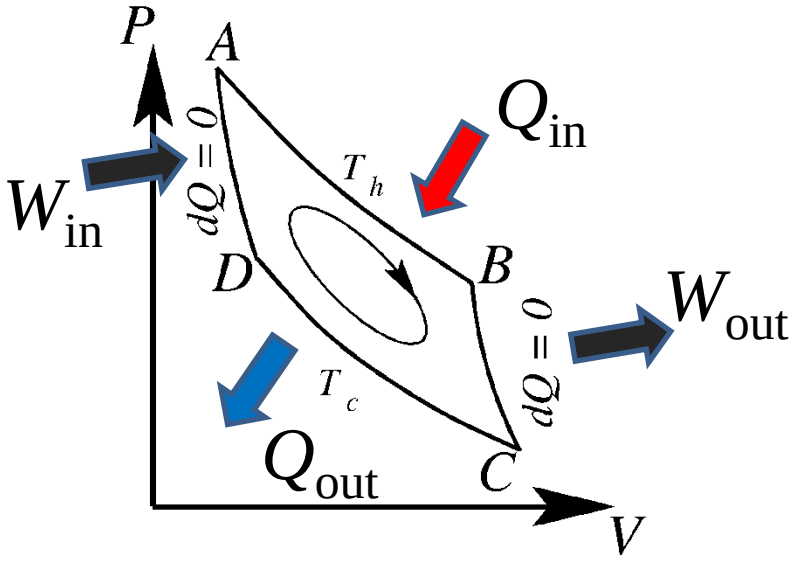


Lecture 6: Steam engines: Carnot cycle

Sadi Carnot
1796-1832

→ **Is the amount of (useful) work limited?**
→ **Is there an alternative medium for steam?**



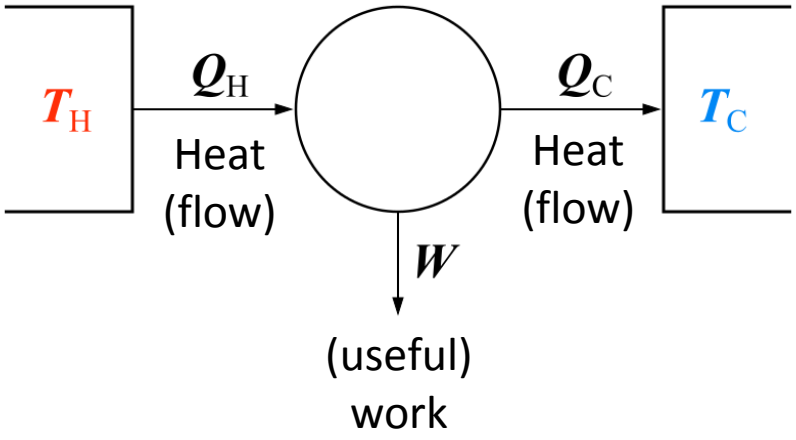


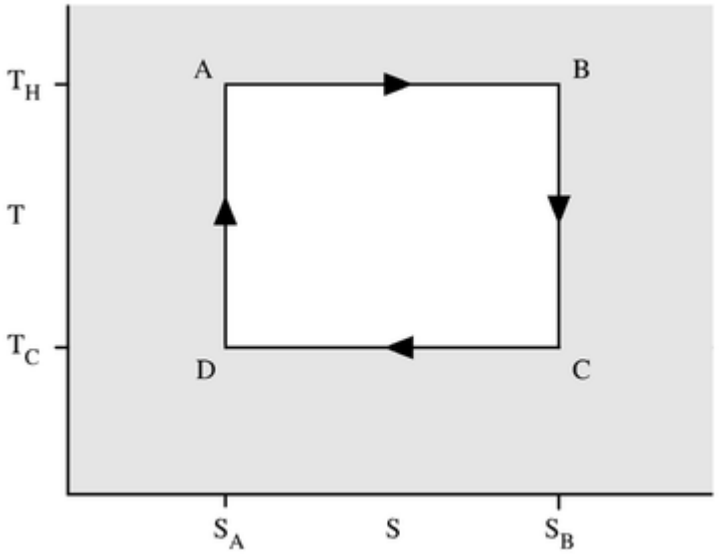
→ T_H **and** T_C **separated: no internal losses**
→ **Process steps: isotherms and adiabats**
→ **Idealized cycle: reversible process**
→ **Arbitrary medium: perfect gas**

Lecture 6: Steam engines: Carnot cycle

Sadi Carnot
1796-1832

→ **Is the amount of (useful) work limited?**
→ **Is there an alternative medium for steam?**





→ T_H and T_C separated: **no internal losses**
→ **Process steps: isotherms and adiabats**
→ **Idealized cycle: reversible process**
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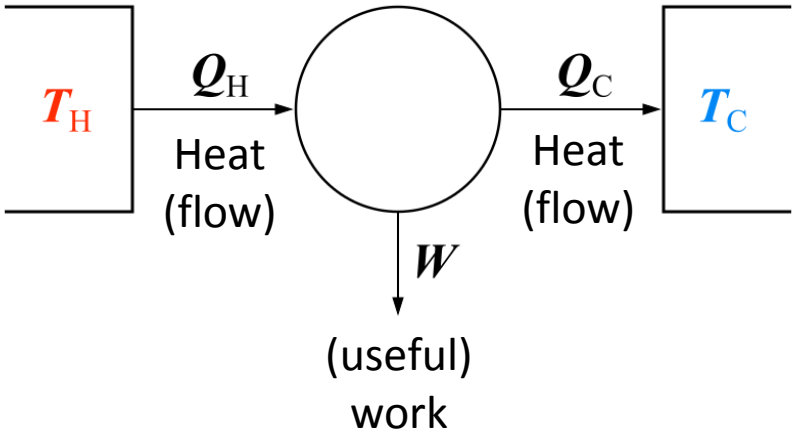
Lecture 6: Steam engines: Carnot cycle

Sadi Carnot
1796-1832

→ **Is the amount of (useful) work limited?**
→ **Is there an alternative medium for steam?**



1824

Transformation of heat into work always involves losses (Q_C)

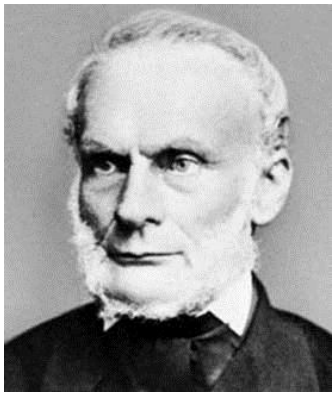
→ T_H **and** T_C **separated: no internal losses**
→ **Process steps: isotherms and adiabats**
→ **Idealized cycle: reversible process**
→ **Arbitrary medium: perfect gas**

Maximal efficiency depends on (T_H -T_C)

Lecture 6: Fundamentals of thermodynamics

First law: conservation of energy *U*

$$dU = dQ + dW$$



Rudolf Clausius
1822-1888

According to this, the second fundamental theorem in the mechanical theory of heat, which in this form might appropriately be called the *theorem of the equivalence of transformations*, may be thus enunciated:

If two transformations which, without necessitating any other permanent change, can mutually replace one another, be called equivalent, then the generation of the quantity of heat Q of the temperature t from work, has the equivalence-value

$$\frac{Q}{T},$$

and the passage of the quantity of heat Q from the temperature t_1 to the temperature t_2, has the value

$$Q\left(\frac{1}{T_2}-\frac{1}{T_1}\right),$$

wherein T is a function of the temperature, independent of the nature of the process by which the transformation is effected.

If, to the last expression, we give the form

$$\frac{Q}{T_2}-\frac{Q}{T_1},$$

R. Clausius *Philosophical Magazine*, 12 (1856) p.81

Second law:
transformations
(processes)

1854

Äquivalenzwert der Verwandlung

Lecture 6: Fundamentals of thermodynamics

Sadi Carnot
1796-1832

Transformation of heat into work always involves losses (Q_C)

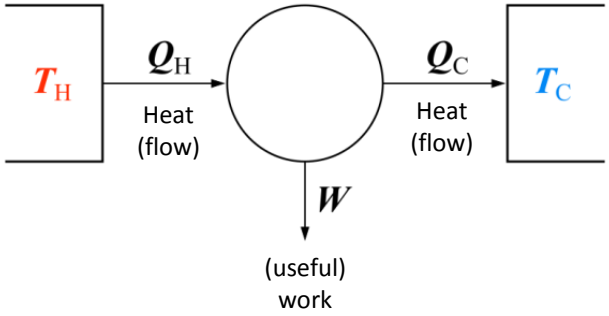
Maximal efficiency depends on (T_H -T_C)

1824

First law: conservation of energy *U*

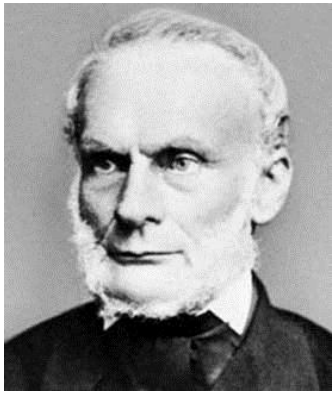
$$dU = dQ + dW$$

Second law: transformations



$$\Delta S = \int \frac{dQ}{T} = 0$$

For all reversible cyclic processes



Rudolf Clausius
1822-1888

1850

1865

Lecture 6: Modern classical thermodynamics

$$\Delta U = Q + W$$

First law: conservation of energy *U*

$$\Delta S^{\text{tot}} = \Delta S + \Delta S^{\text{sur}} \geq 0$$

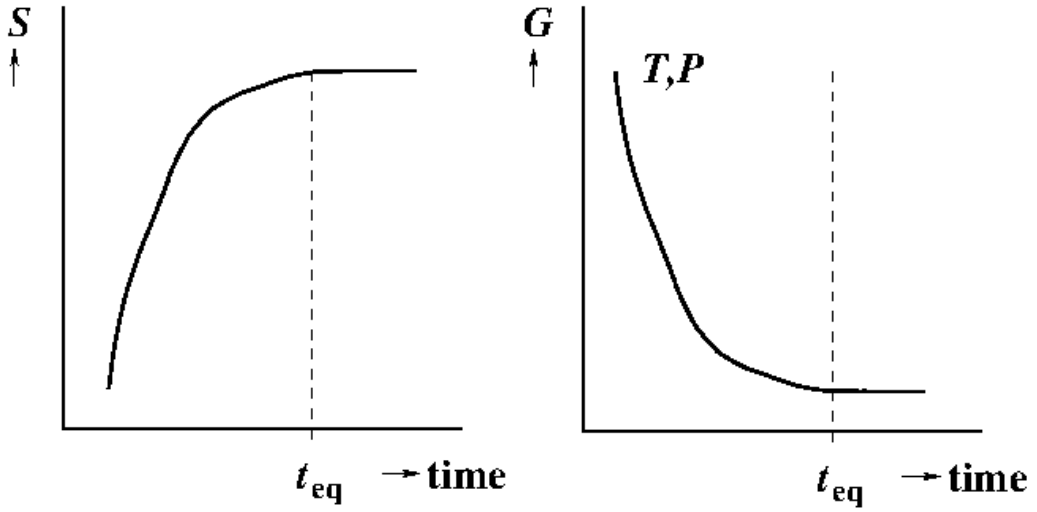
Second law: processes

$$dS = \frac{dQ^{\text{rev}}}{T}$$

The entropy (spontaneously) always increases until thermodynamic equilibrium is reached

ENTROPY
‖
Heat
+
Temperature

$$\Delta S^{\text{sur}} = \frac{-Q}{T}$$

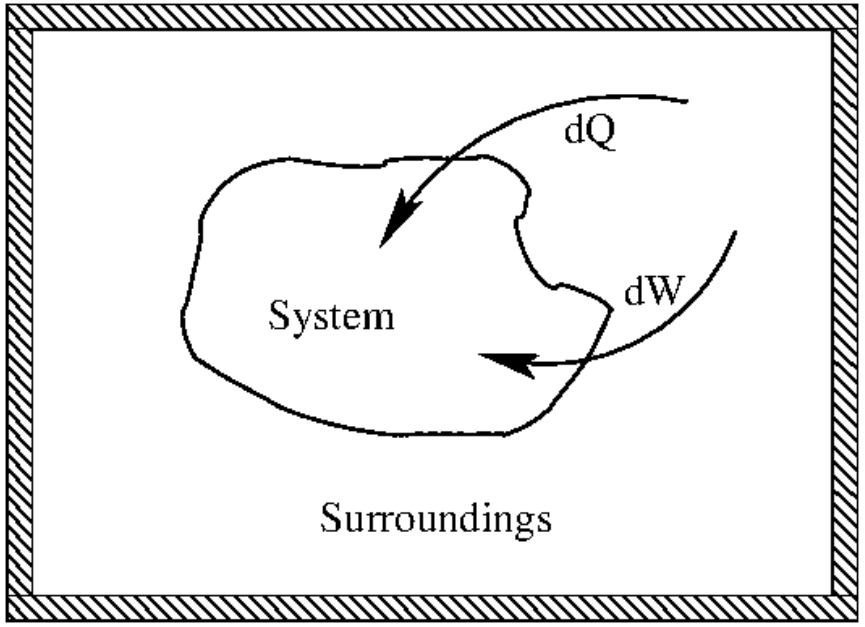


Lecture 6: Modern classical thermodynamics

$$\Delta U = Q + W$$

$$\Delta S^{\text{tot}} = \Delta S + \Delta S^{\text{sur}} \geq 0$$

$$dS = \frac{dQ^{\text{rev}}}{T}$$



for any spontaneous process:

$$\Delta S^{\text{sur}} = \frac{-Q}{T} \Rightarrow dS_{\text{tot}} = dS - \frac{dQ}{T} \geq 0 \Rightarrow TdS \geq dQ$$

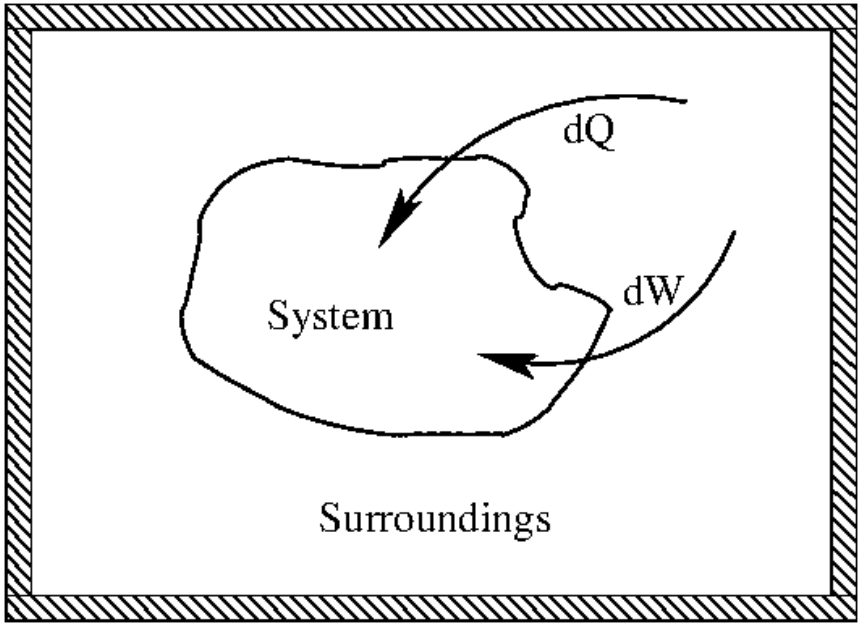
$$\Rightarrow dQ \leq TdS$$ **Clausius inequality**

Lecture 6: Modern classical thermodynamics

Clausius inequality

$$dQ \leq TdS$$

$$\Rightarrow \begin{cases} dQ^{\text{rev}} = TdS \\ dQ^{\text{irr}} < TdS \end{cases}$$



$$\Rightarrow dU = dQ + dW = dQ^{\text{irr}} - P_{\text{ext}}\,dV = TdS - PdV$$

any process | **irr. Process** (mech. Work) | **rev. Process** (mech. Work)

***U* is a state function, so independent of the path**

Lecture 6: Fundamentals of thermodynamics

Hermann von Helmholtz
1821-1894

$$dU = dQ + dW$$

Helmholtz free energy

$$A \equiv U - TS$$

$$dA = dU - d(TS)$$

$$dQ \le TdS$$

$$dA = dQ + dW - SdT - TdS \le dW - SdT$$

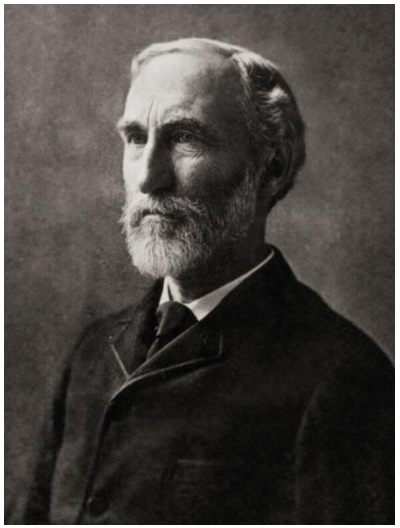
$$dA\big|_T \le dW$$

$dW < 0$ **for work done by the system on surroundings**

$$W_{\max} = \Delta A\big|_T$$

An isothermal reversible process delivers maximal (volume) work

Lecture 6: Fundamentals of thermodynamics



Josiah Gibbs
1839-1903

$$dU = dQ + dW$$

$$G \equiv H - TS$$

$$dG = dH - d(TS)$$

$$dQ \le TdS$$

$$dG\big|_P = dQ - TdS - SdT + dW_e \quad \Rightarrow \quad dG\big|_P \le -SdT + dW_e$$

$$dG\big|_{P,T} \le dW_e$$

(Study guide: p.12)

$$W_e^{\max} = \Delta G\big|_{P,T}$$

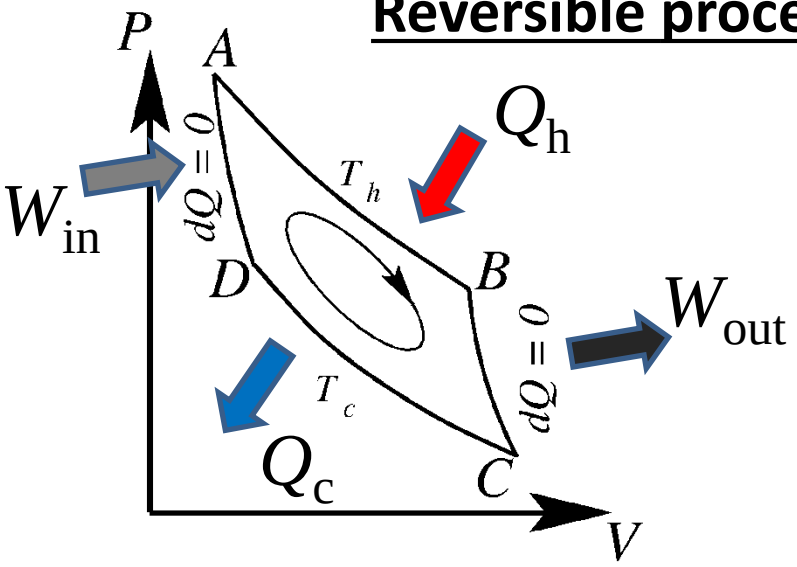
Isothermal isobaric reversible process delivers maximal (electric) work

Lecture 6: Energy conversion: Carnot cycle

Sadi Carnot
(1796-1832)

Carnot cycle

Reversible processes



Machine model:

→ cyclic process

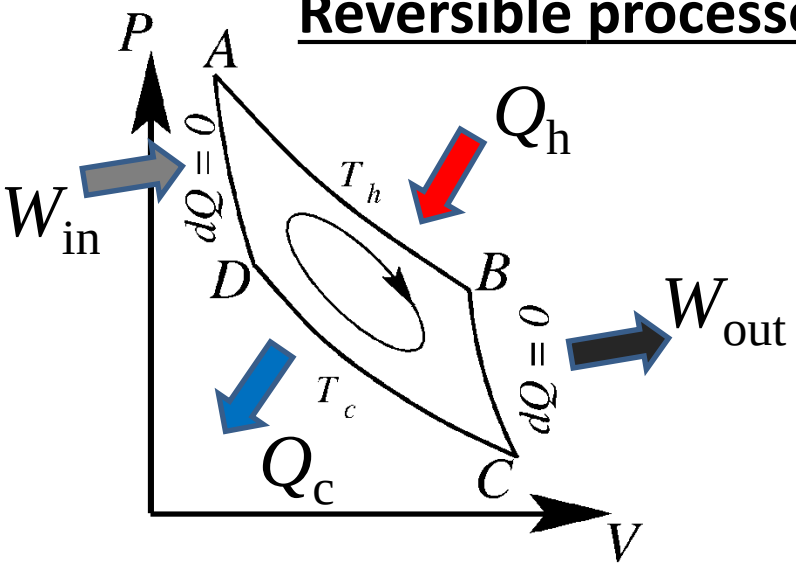
$$Q \rightarrow W$$

for a steam engine

Lecture 6: Energy conversion: Carnot cycle

Carnot cycle

Reversible processes



Machine model:

→ cyclic process

$$Q \rightarrow W$$

for a steam engine

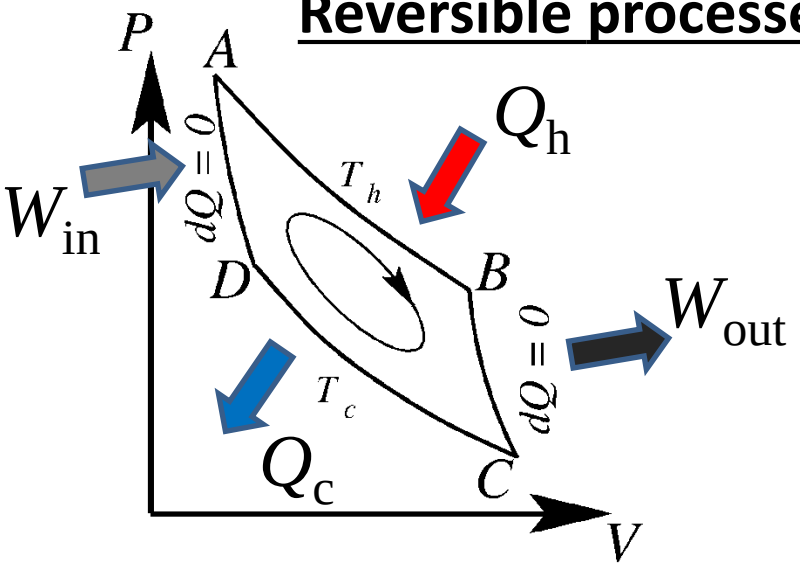
or power station

Heat engine

Lecture 6: Energy conversion: Carnot cycle

Carnot cycle

Reversible processes



Machine model:

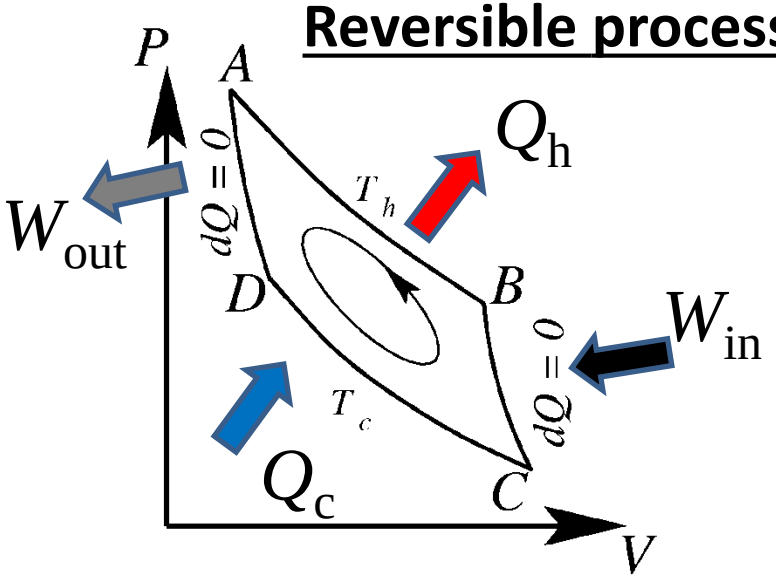
→ cyclic process

$$Q \rightarrow W$$

Heat engine

Carnot cycle

Reversible processes



Machine model:

→ cyclic process

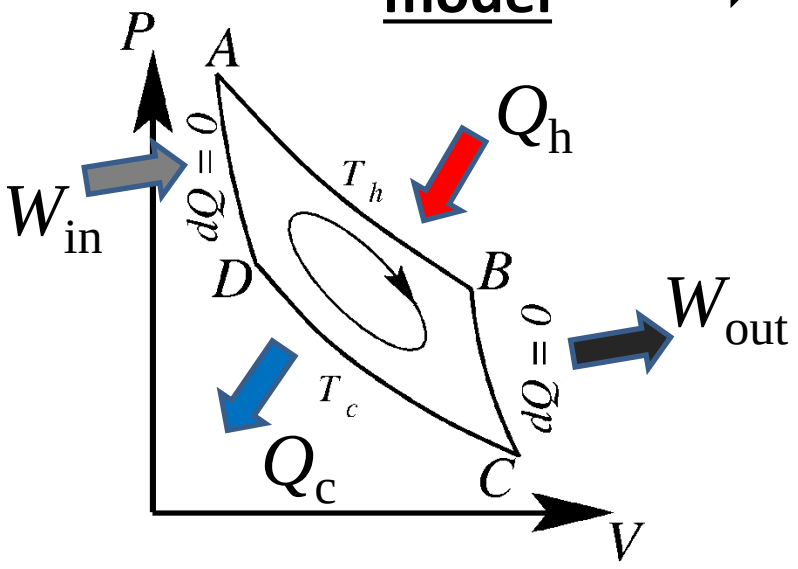
$$W \rightarrow Q$$

for a refrigerator or heat pump

Lecture 6: Energy conversion: Carnot cycle

Study Guide p. 19-22

Reversible model



$$\int_B^C dS = \int_B^C \frac{dQ^{rev}}{T} = 0 = \int_D^A dS$$

$$\int_A^B dS = \int_A^B \frac{dQ^{rev}}{T_h} = \frac{Q_h}{T_h}$$

$$\int_C^D dS = \int_C^D \frac{dQ^{rev}}{T_c} = \frac{Q_c}{T_c}$$

$$\oint dS = 0$$

***S* is state function**

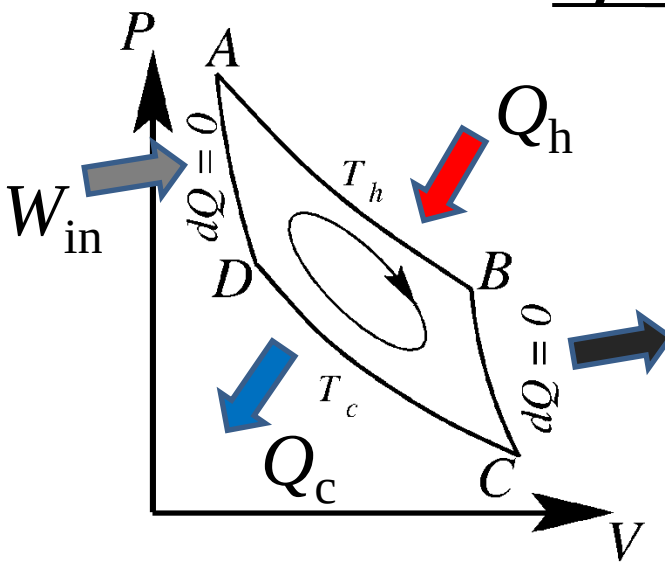
For a (reversible) Carnot cycle

$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

Lecture 6: Energy conversion: Carnot cycle

U is state function

Cyclic process ⇒ $\oint dU = 0$



$$\oint dW = -\oint dQ = -(Q_h + Q_c)$$

$Q_c < 0, Q_h > 0$ **and** $Q_h + Q_c > 0$

(cf. exercise 4 for gasses)

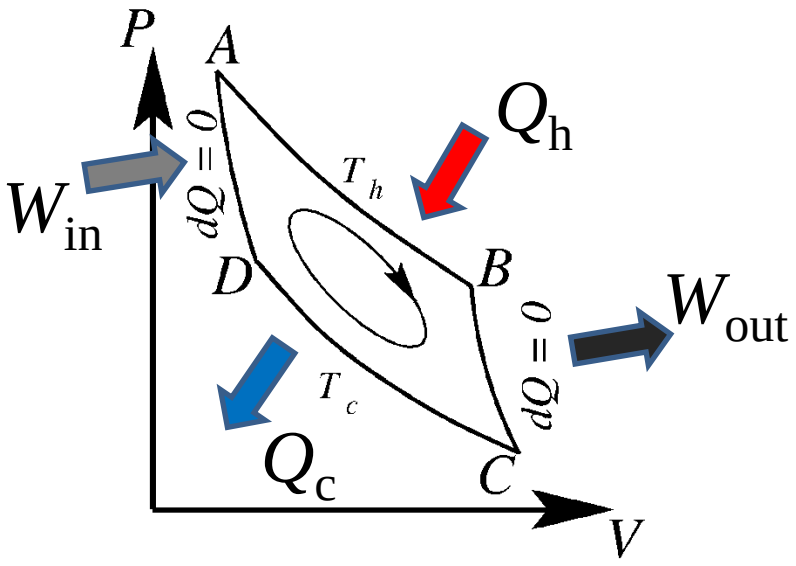
⇒ $\oint dW = W_{out} + W_{in} = -(Q_h + Q_c) < 0$

Net work is done by the system on surroundings

Lecture 6: Energy conversion: Carnot cycle

U is state function

Cyclic process ⇒ $\oint dU = 0$



$$W = \oint dW < 0$$

Net work is done by the system on surroundings

$$\Delta S = \oint dS = 0$$

$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

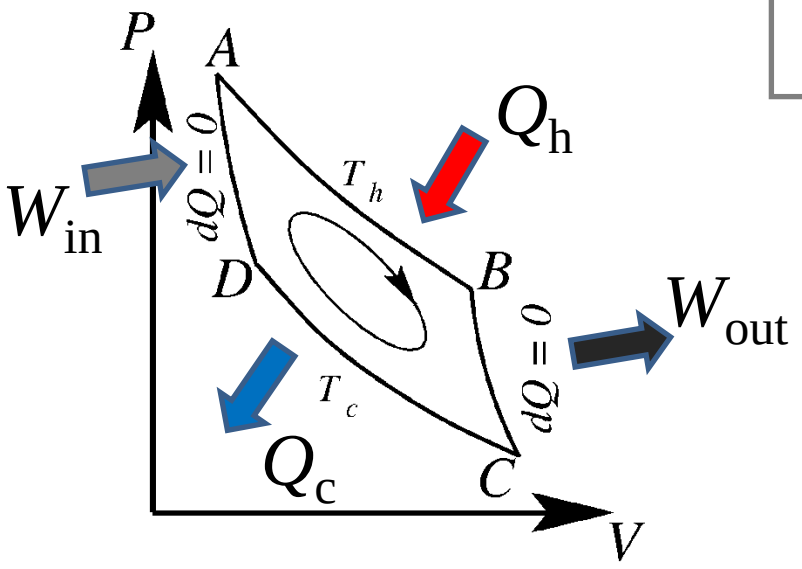
$$\Delta S^{tot} = \Delta S^{sur} + \Delta S = \Delta S^{sur} = -\frac{Q_h}{T_h} - \frac{Q_c}{T_c} = 0$$

"equilibrium" process

Lecture 6: Conversion efficiency: Carnot cycle

Efficiency of the process:

$$\eta \equiv \frac{\text{useful energy}}{\text{energy cost}} = \frac{|W|}{|Q_h|} \quad (\text{x } 100\,\%)$$



$$\eta = \frac{|(Q_h + Q_c)|}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|}$$

$(Q_c < 0)$

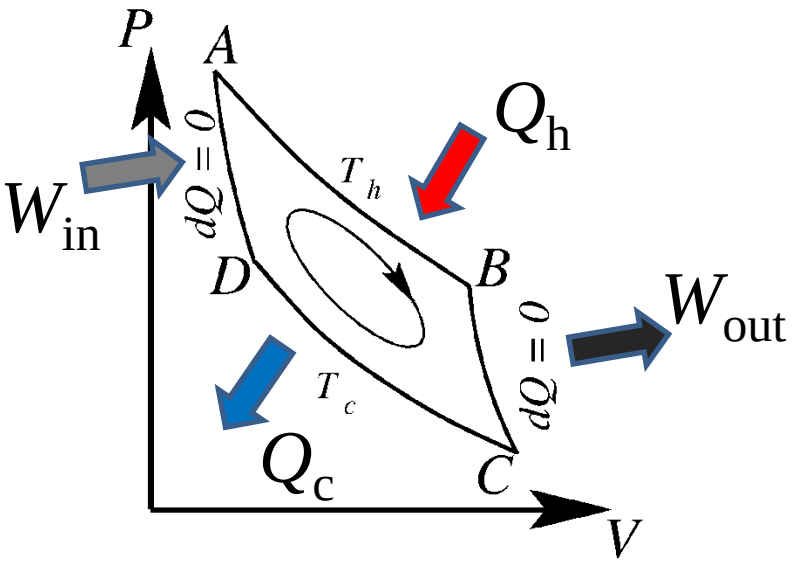
$$\eta = 1 - \frac{|Q_c|}{|Q_h|}$$

Carnot cycle

$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

$$\eta = 1 - \frac{T_c}{T_h}$$

Lecture 6: Conversion efficiency: Carnot cycle



Thermodynamic efficiency of a Carnot cycle

$$\eta = 1 - \frac{T_c}{T_h} \qquad (T_c \le T_h)$$

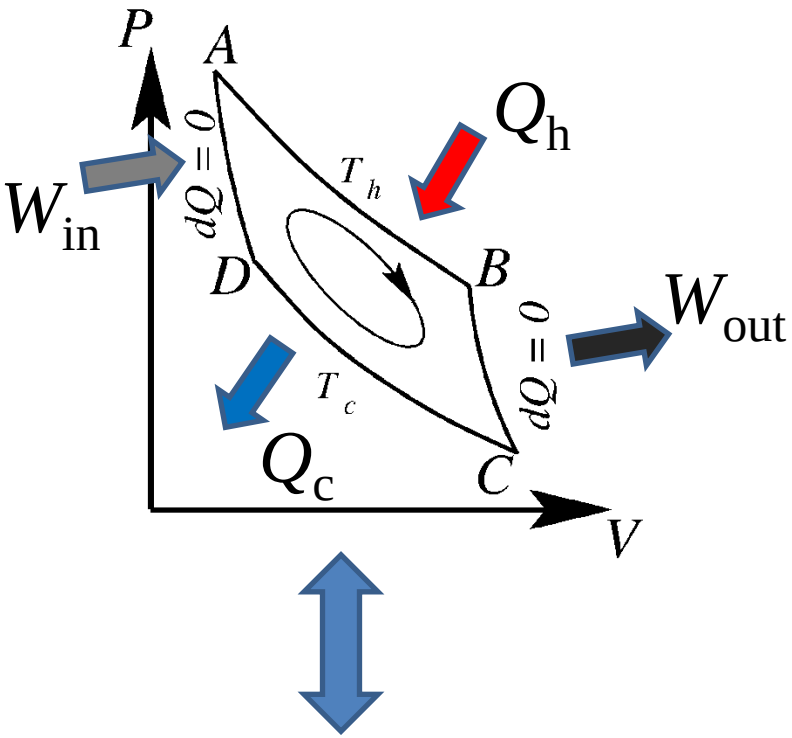
$$\eta \xrightarrow[T_c \uparrow T_h]{} 0 \qquad \eta \xrightarrow[T_c \downarrow 0]{} 1$$

$$\eta \xrightarrow[T_h \to \infty]{} 1$$

Power station

$$\begin{cases} T_h \approx 500\,^{\circ}\mathrm{C}\ \text{(steam)} \\ T_c \approx 100\,^{\circ}\mathrm{C}\ \text{(dumped)} \end{cases} \Rightarrow \eta \approx 52\%$$

Lecture 6: Conversion efficiency: Carnot cycle



Thermodynamic efficiency of a Carnot cycle

$$\eta = 1 - \frac{T_c}{T_h} \qquad \left(T_c \le T_h\right)$$

$$\eta \xrightarrow[T_c \uparrow T_h]{} 0 \qquad \eta \xrightarrow[T_c \downarrow 0]{} 1$$

$$\eta \xrightarrow[T_h \to \infty]{} 1$$

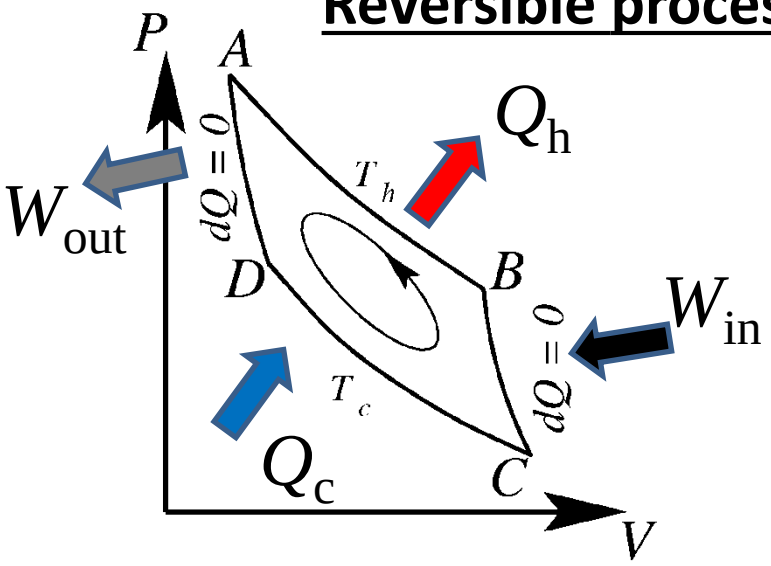
Reversible process ➡ **Irreversible process:** $\left(dA\big|_T < dW\right)$

$$\eta < 1 - \frac{T_c}{T_h}$$

Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



Machine model:

→ cyclic process

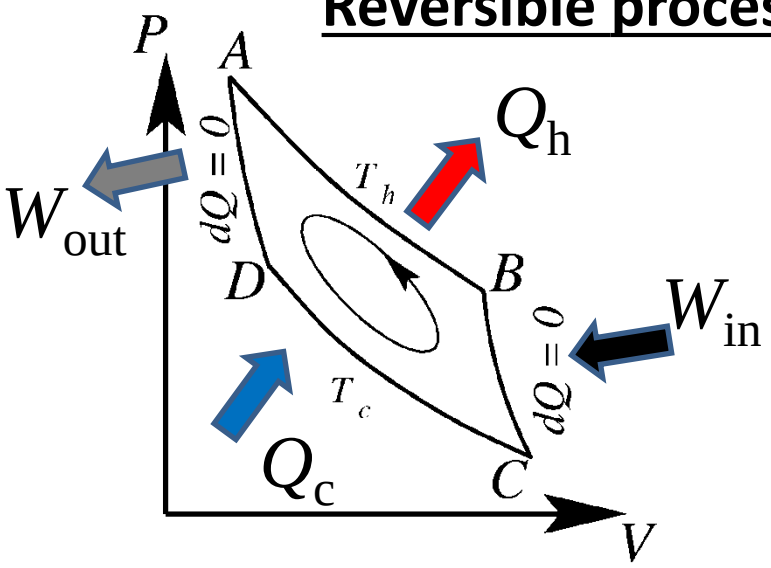
$$W \rightarrow Q$$

for a refrigerator or heat pump

Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



$$\int_A^D dS = \int_A^D \frac{dQ^{rev}}{T} = 0 = \int_C^B dS$$

$$\int_D^C dS = \int_D^C \frac{dQ^{rev}}{T_c} = \frac{Q_c}{T_c}$$

$$\int_B^A dS = \int_B^A \frac{dQ^{rev}}{T_h} = \frac{Q_h}{T_h}$$

$$\oint dS = 0$$

S is state function

Machine model:

→ cyclic process

$W \rightarrow Q$

for a refrigerator or heat pump

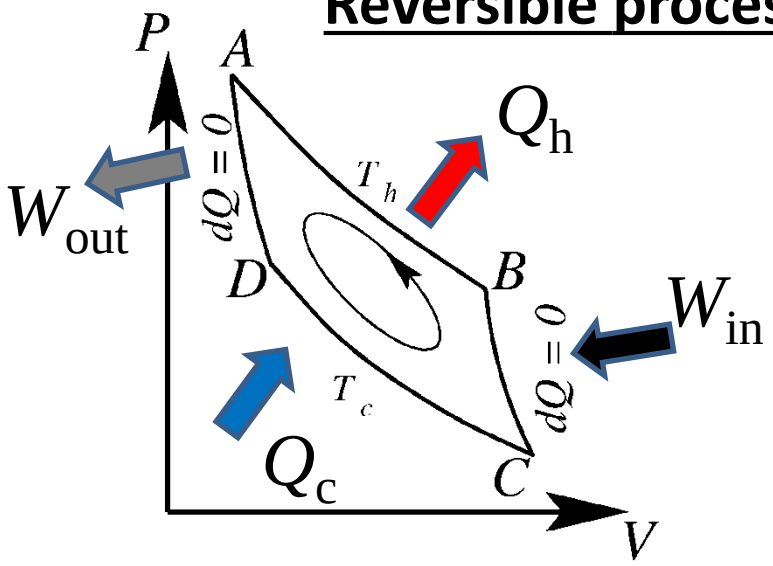
$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

$$\Delta S^{tot} = 0$$

Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



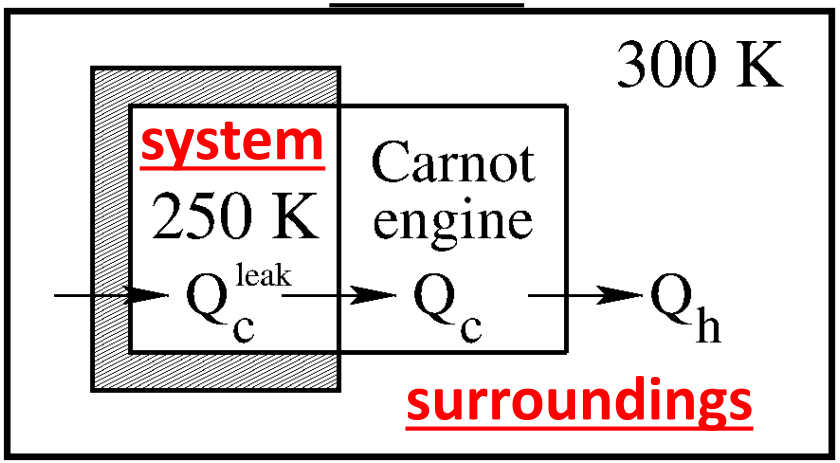
Machine model:

→ cyclic process

$$W \rightarrow Q$$

for a refrigerator or heat pump

Freezer



$Q_h < 0, Q_c > 0$ **and** $Q_h + Q_c < 0$

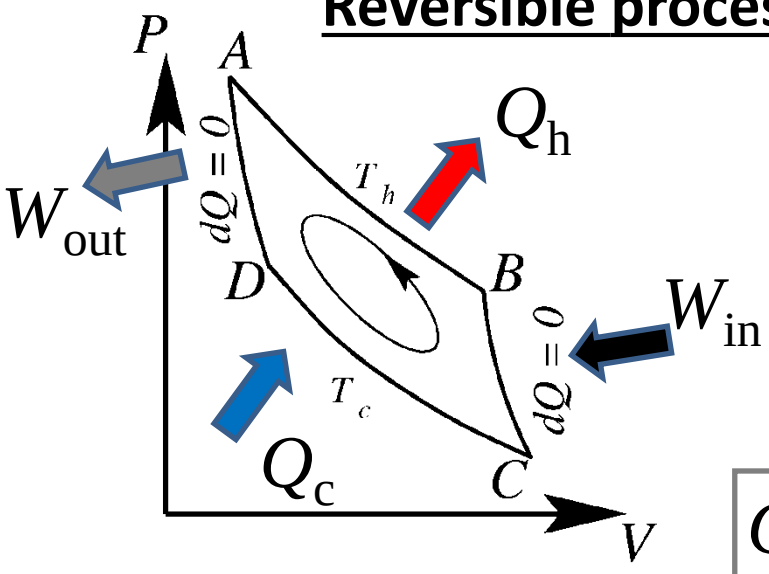
$$\Delta S^{tot} = \Delta S^{sur} = \frac{|Q_h|}{T_h} - \frac{|Q_c|}{T_h} < 0$$

Non-spontaneous process

Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



Machine model:

→ cyclic process

$W \rightarrow Q$

for a refrigerator or heat pump

U is state function

$$\oint dU = 0$$

$$\oint dW = -\oint dQ = -(Q_h + Q_c)$$

$Q_h < 0, Q_c > 0$ **and** $Q_h + Q_c < 0$

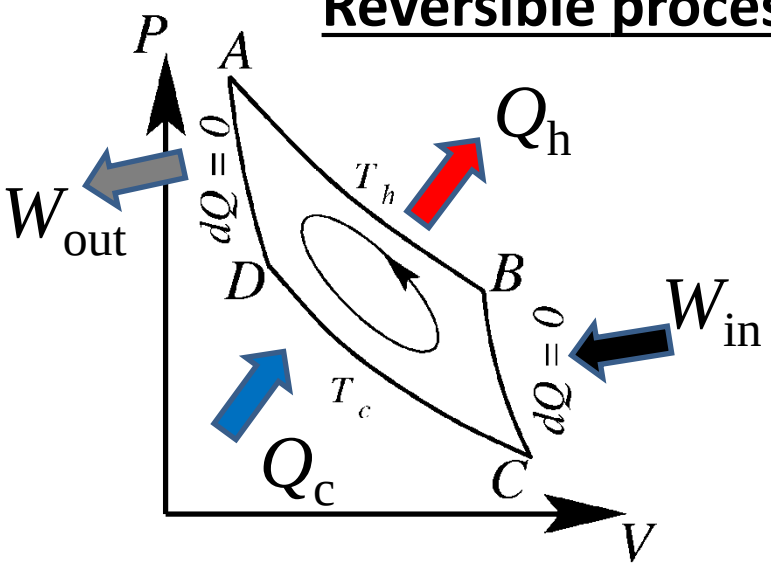
$$W = -(Q_h + Q_c) > 0$$

Work has to be done to run the process

Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



Machine model:

→ cyclic process

$$W \rightarrow Q$$

for a refrigerator or heat pump

$$W = -(Q_h + Q_c) > 0$$

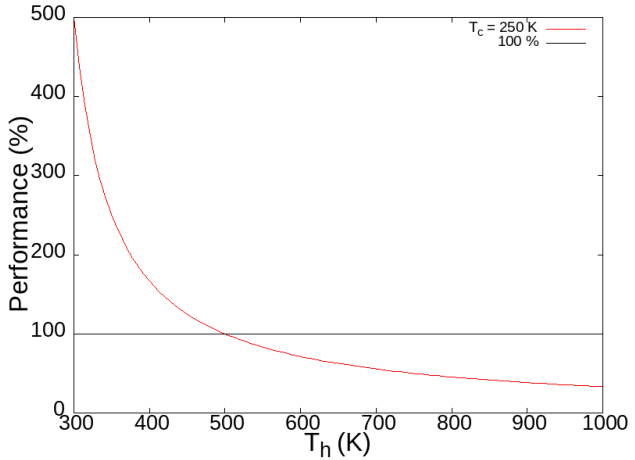
Non spontaneous (forced) process

Refrigerator:

$$\eta \equiv c = \frac{|Q_c|}{|W|} = \frac{|Q_c|}{|Q_h| - |Q_c|} = \frac{T_c}{T_h - T_c}$$

$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

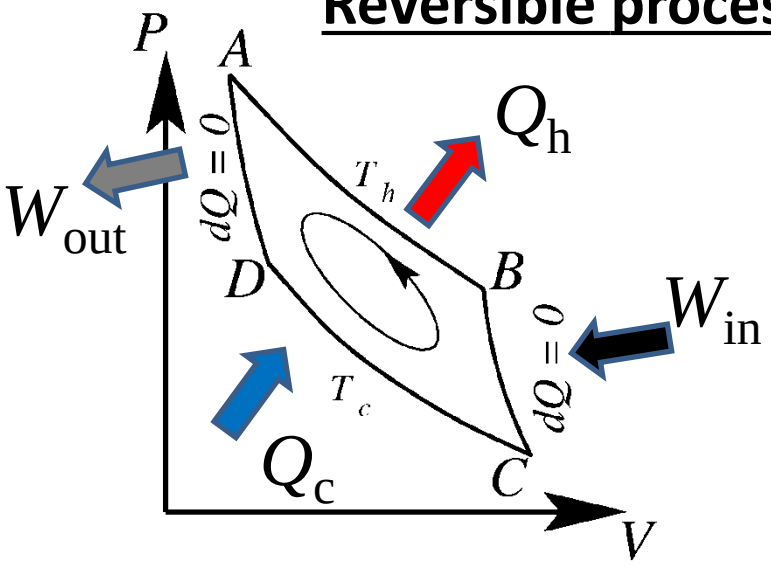
***c*: performance**



Lecture 6: Conversion efficiency: Carnot cycle

Inverse Carnot cycle

Reversible processes



Machine model:

→ cyclic process

$$W \rightarrow Q$$

for a refrigerator or heat pump

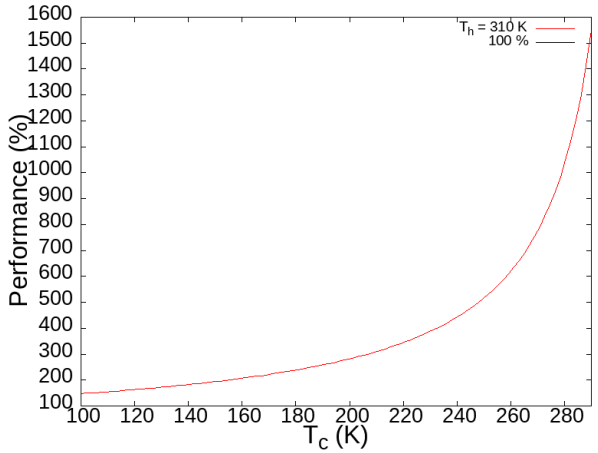
$$W = -(Q_h + Q_c) > 0$$

Non spontaneous (forced) process

Heat pump:

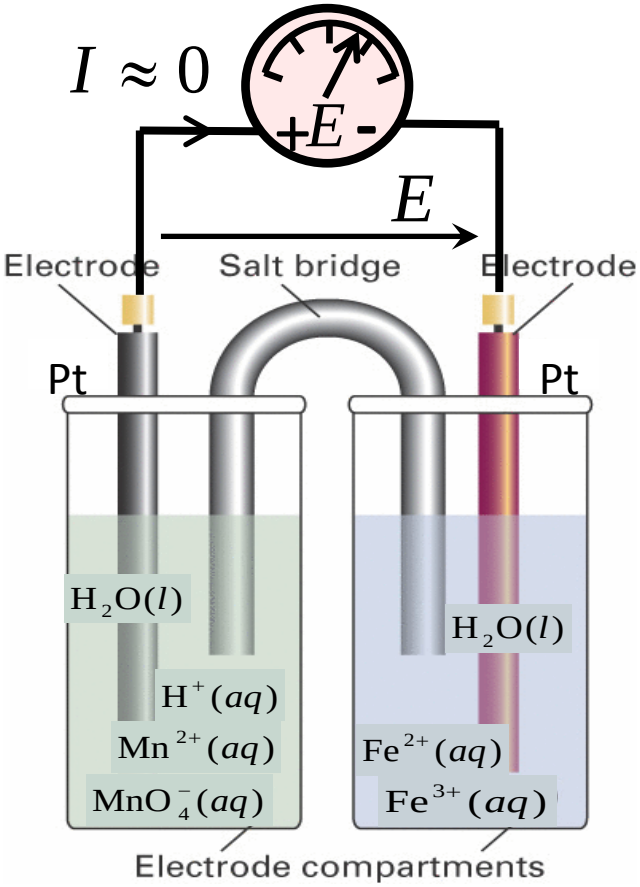
$$\eta \equiv c = \frac{|Q_h|}{|W|} = \frac{|Q_h|}{|Q_h| - |Q_c|} = \frac{T_h}{T_h - T_c}$$

c: performance



$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

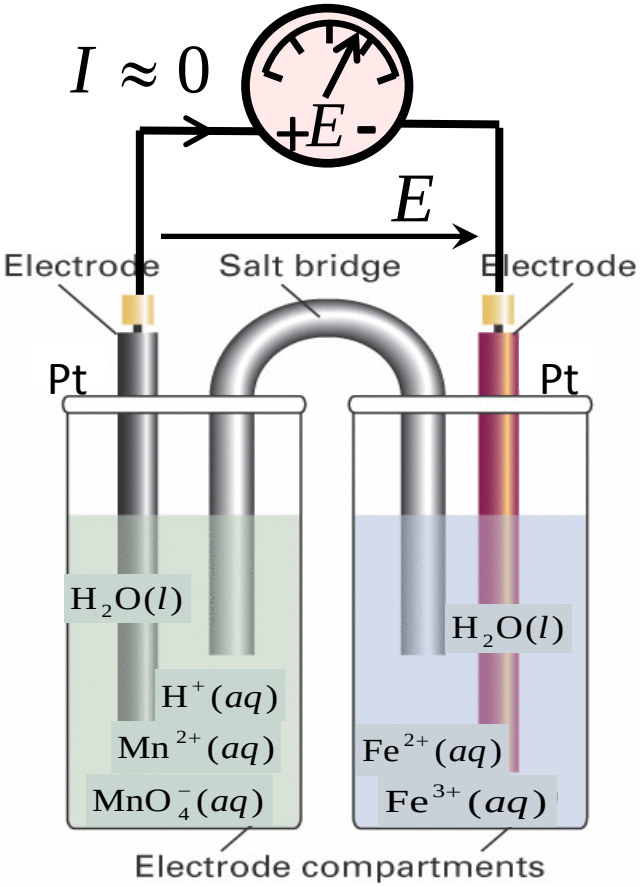
Lecture 6: Conversion efficiency: Batteries



$$E = E^{\Theta} - \frac{RT}{\nu F} \ln Q$$

Nernst equation

Lecture 6: Conversion efficiency: Batteries



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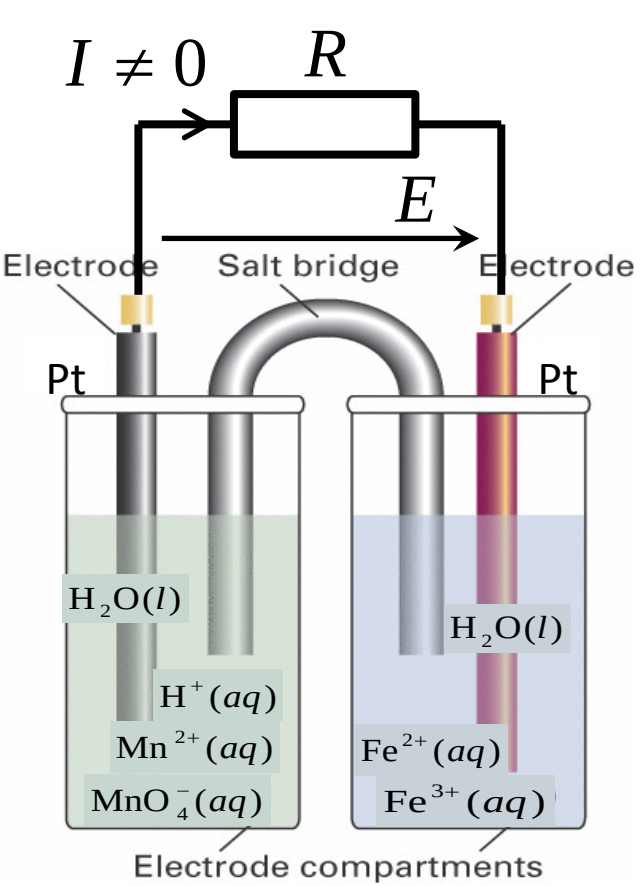
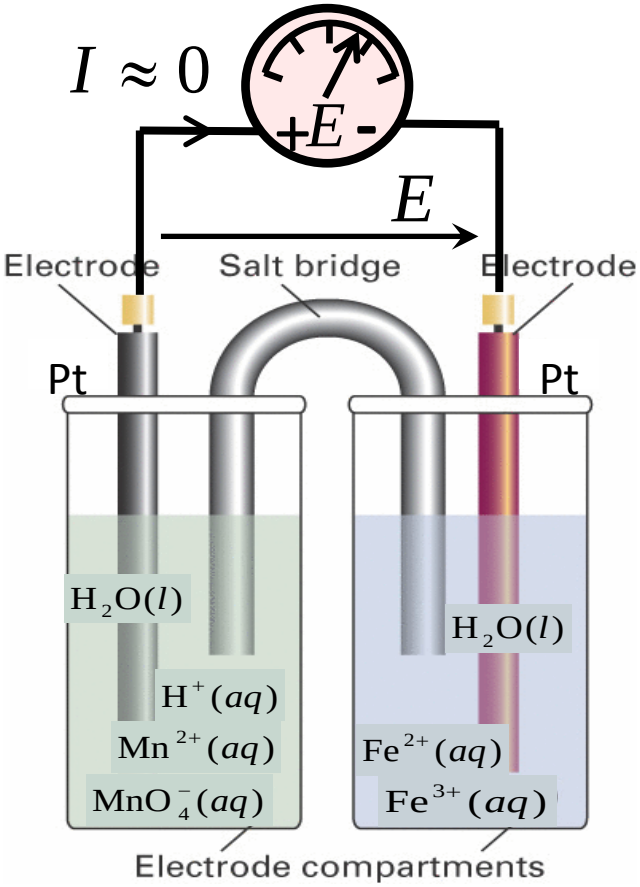


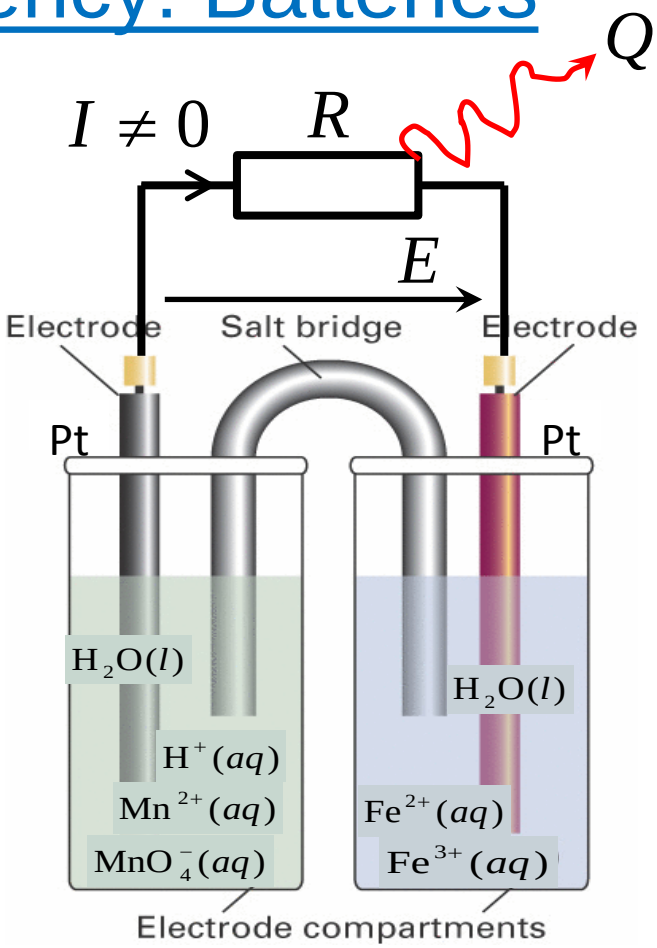
$$E = ?$$

Lecture 6: Conversion efficiency: Batteries



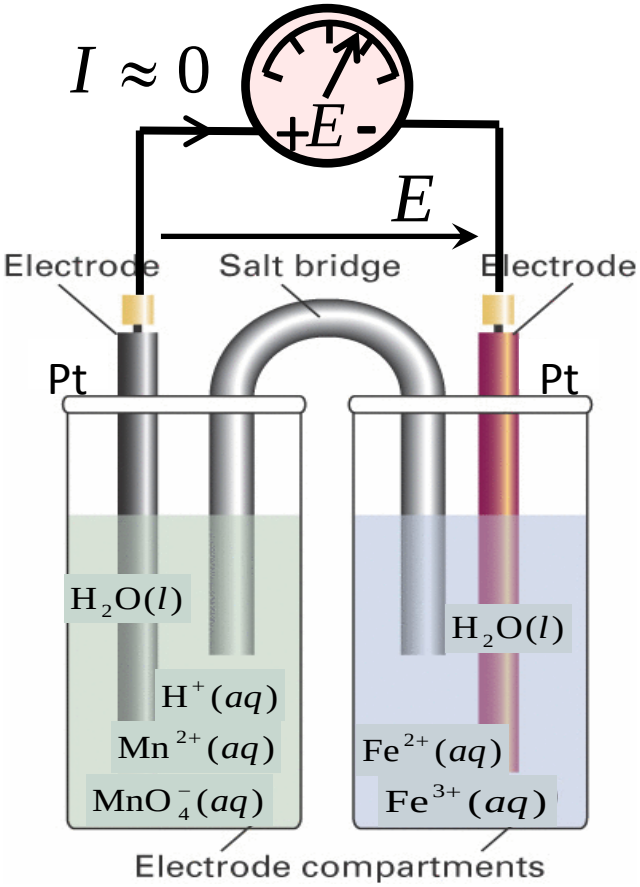
$$E = E^{\Theta} - \frac{RT}{\nu F} \ln Q$$

Nernst equation



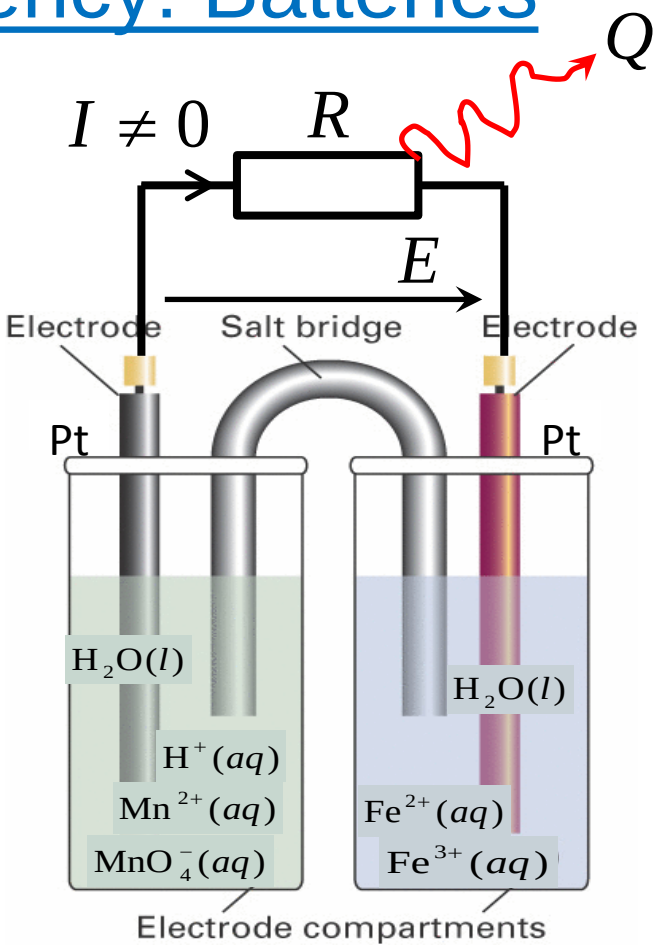
$$E = ?$$

Lecture 6: Conversion efficiency: Batteries



$$E = E^{\Theta} - \frac{RT}{\nu F} \ln Q$$

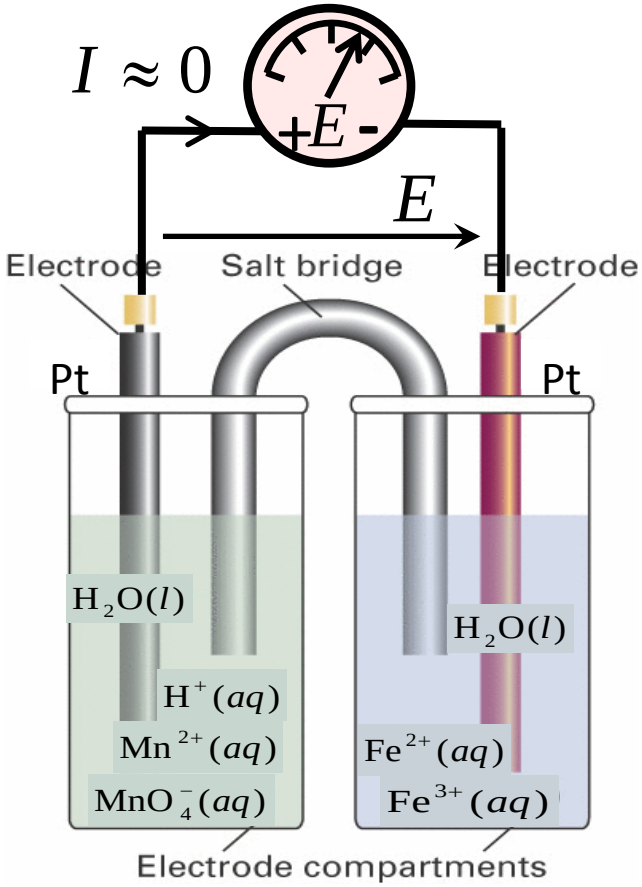
Nernst equation



$E = ?$

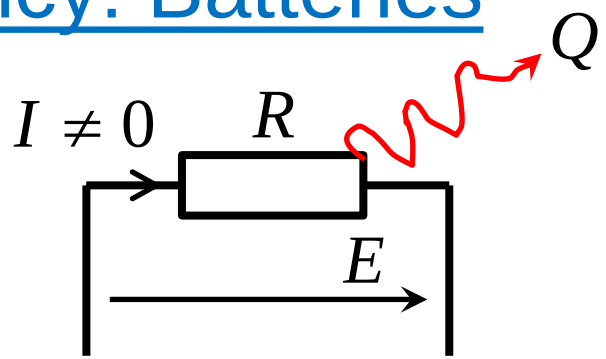
$\eta = ?$

Lecture 6: Conversion efficiency: Batteries



$$E = E^{\Theta} - \frac{RT}{\nu F}\ln Q$$

Nernst equation



$$\eta \equiv \frac{\text{useful energy}}{\text{energy cost}} = \frac{\left|\int dQ\right|}{\left|\int dW_e\right|} = 1$$

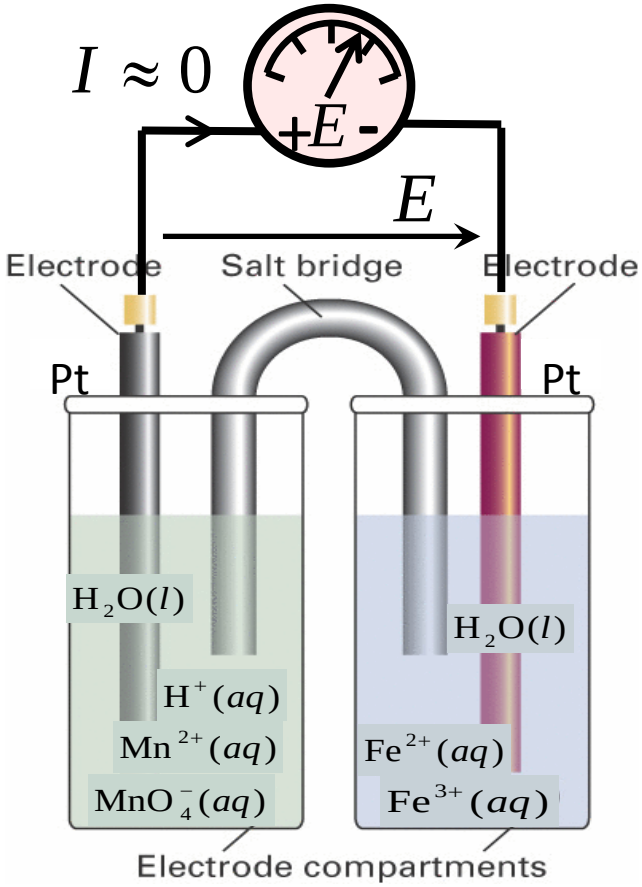
Joule heating:

100 % conversion

$$\int dQ = \int P_e dt = \int IE\,dt = \int \frac{E^2}{R} dt$$

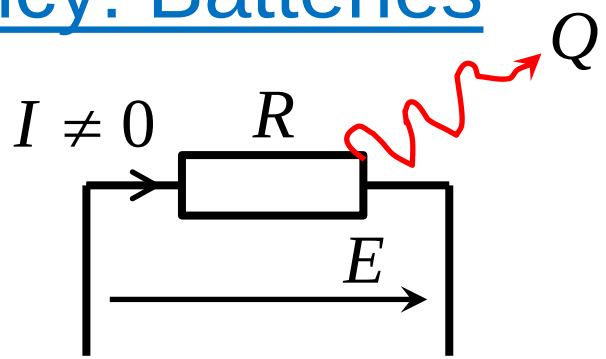
$$E = IR$$

Lecture 6: Conversion efficiency: Batteries



$$E = E^{\Theta} - \frac{RT}{\nu F}\ln Q$$

Nernst equation



$$\eta \equiv \frac{\text{useful energy}}{\text{energy cost}} = \frac{\left|\int dQ\right|}{\left|\int dW_e\right|} = 1$$

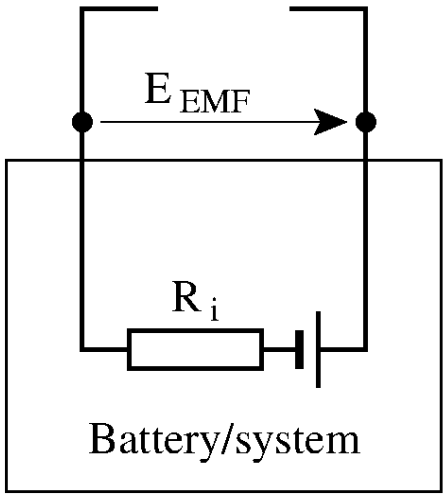
Joule heating:

100 % conversion

$$\int dQ = \int P_e dt = \int IE\,dt = \int \frac{E^2}{R} dt$$

$E = ?$ ⟸ $E = IR$

Lecture 6: Conversion efficiency: Batteries



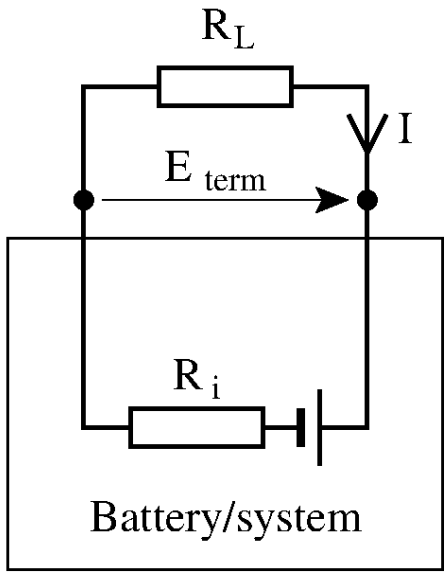
EMF:

ElectroMotive Force

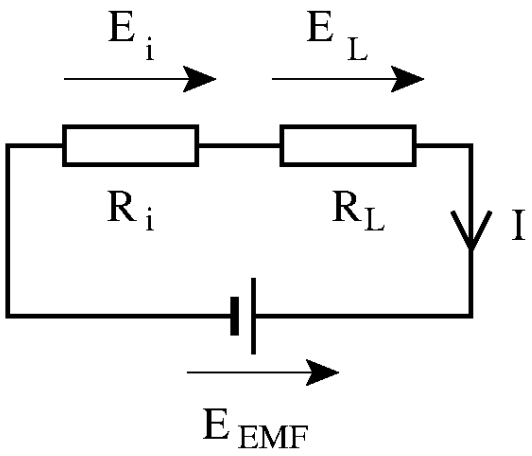
$$E_{\mathrm{EMF}} = E^{\Theta} - \frac{RT}{\nu\,\mathrm{F}} \ln Q$$

Nernst equation

$$\left(E_{\mathrm{EMF}} = E_{\mathrm{cell}}\right)$$



$$E_{\mathrm{term}} = E_{\mathrm{L}} = IR_{\mathrm{L}}$$

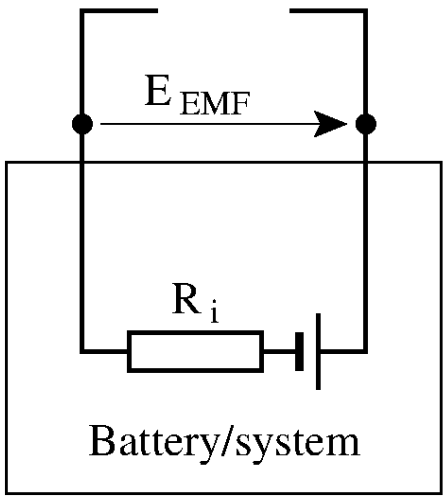


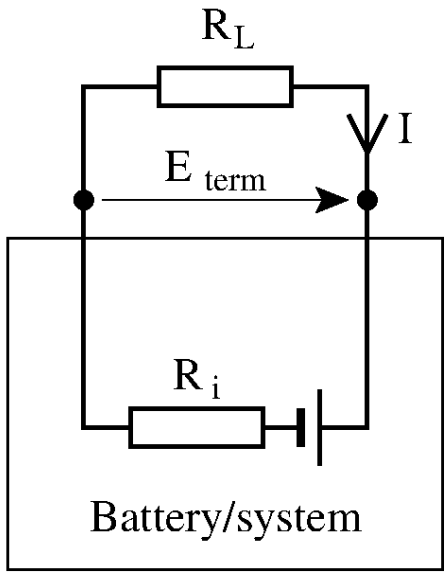
$$E_{\mathrm{EMF}} = E_{\mathrm{i}} + E_{\mathrm{L}}$$

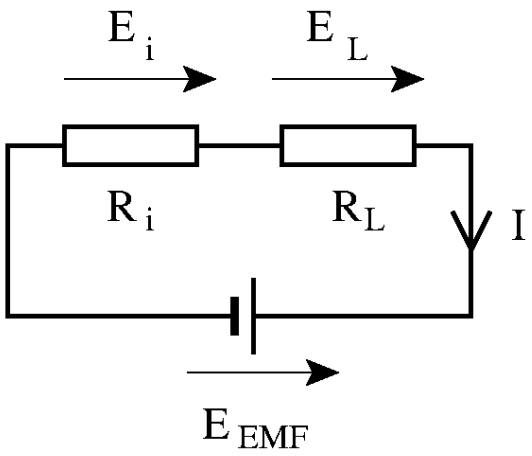
$$E_{\mathrm{EMF}} = IR_{\mathrm{i}} + IR_{\mathrm{L}}$$

$$I = \frac{E_{\mathrm{EMF}}}{R_{\mathrm{i}} + R_{\mathrm{L}}}$$

Lecture 6: Conversion efficiency: Batteries







EMF:

ElectroMotive Force

$$E_{\mathrm{EMF}} = E^{\Theta} - \frac{RT}{\nu\,\mathrm{F}} \ln Q$$

Nernst equation

$$\left(E_{\mathrm{EMF}} = E_{\mathrm{cell}}\right)$$

$$E_{\mathrm{term}} = E_{\mathrm{L}} = IR_{\mathrm{L}}$$

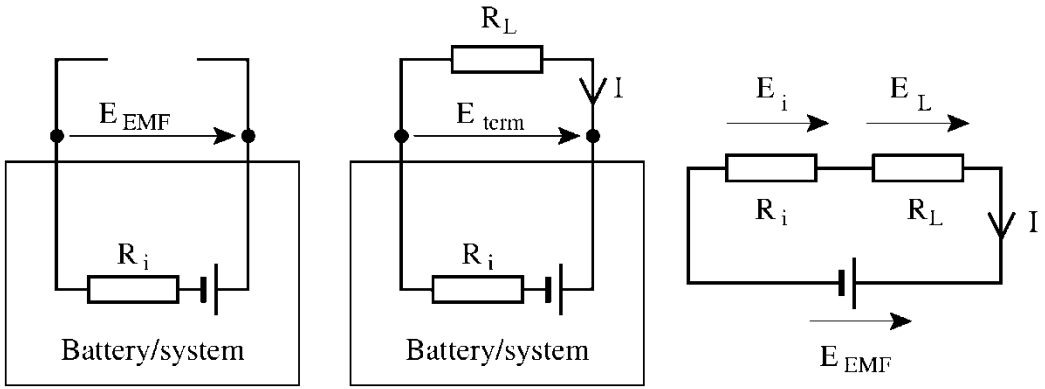
$$E_{\mathrm{L}} = E_{\mathrm{EMF}} \frac{R_{\mathrm{L}}}{R_{\mathrm{i}} + R_{\mathrm{L}}}$$

$$E_{\mathrm{EMF}} = E_{\mathrm{i}} + E_{\mathrm{L}}$$

$$E_{\mathrm{EMF}} = IR_{\mathrm{i}} + IR_{\mathrm{L}}$$

$$I = \frac{E_{\mathrm{EMF}}}{R_{\mathrm{i}} + R_{\mathrm{L}}}$$

Lecture 6: Conversion efficiency: Batteries



$$E_{\mathrm{EMF}} = E^{\Theta} - \frac{RT}{\nu\,\mathrm{F}} \ln Q$$

Nernst equation

$$\left(E_{\mathrm{EMF}} = E_{\mathrm{cell}}\right)$$

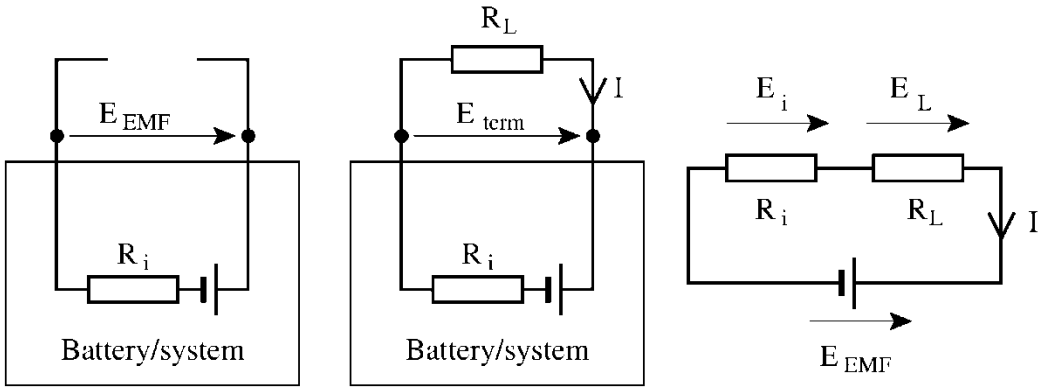
$$E_{\mathrm{L}} = E_{\mathrm{EMF}} \frac{R_{\mathrm{L}}}{R_{\mathrm{i}} + R_{\mathrm{L}}}$$

$$\int dQ_{\mathrm{L}} = \int \frac{E_{\mathrm{L}}^2}{R_{\mathrm{L}}} dt = \frac{E_{\mathrm{L}}^2}{R_{\mathrm{L}}} \Delta t$$

$E_{\mathrm{L}} \approx$ constant

$$\eta = \frac{\left|\int dQ_{\mathrm{L}}\right|}{\left|\int dW_{\mathrm{e}}\right|} = \frac{Q_{\mathrm{L}}}{\mathrm{W_e}}$$

Lecture 6: Conversion efficiency: Batteries



$$E_{\mathrm{EMF}} = E^{\Theta} - \frac{RT}{\nu\,\mathrm{F}} \ln Q$$

Nernst equation

$$\left(E_{\mathrm{EMF}} = E_{\mathrm{cell}}\right)$$

$$E_{\mathrm{L}} = E_{\mathrm{EMF}} \frac{R_{\mathrm{L}}}{R_{\mathrm{i}} + R_{\mathrm{L}}}$$

$$\int dQ_{\mathrm{L}} = \int \frac{E_{\mathrm{L}}^2}{R_{\mathrm{L}}} dt = \frac{E_{\mathrm{L}}^2}{R_{\mathrm{L}}} \Delta t$$

$E_{\mathrm{L}} \approx$ constant

$$\Delta t = \nu F / I$$

$$\int dW_{\mathrm{e}} = \int \Delta_{\mathrm{r}} G dt = \Delta_{\mathrm{r}} G \Delta t$$

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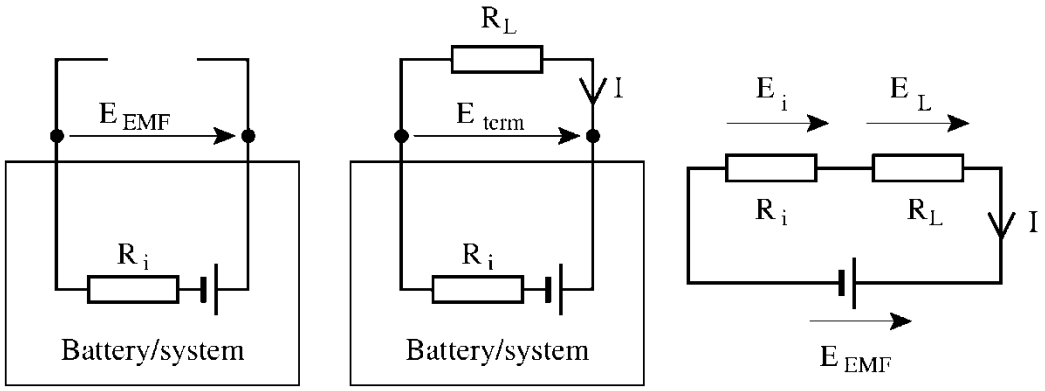

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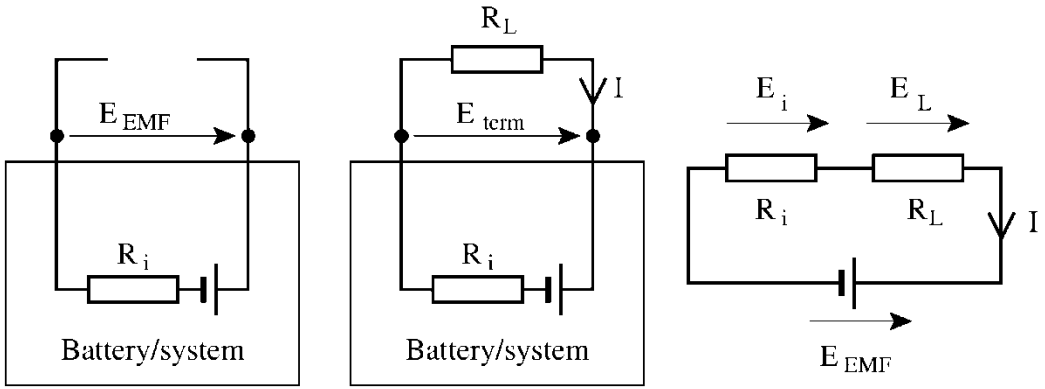
Lecture 6: Conversion efficiency: Batteries



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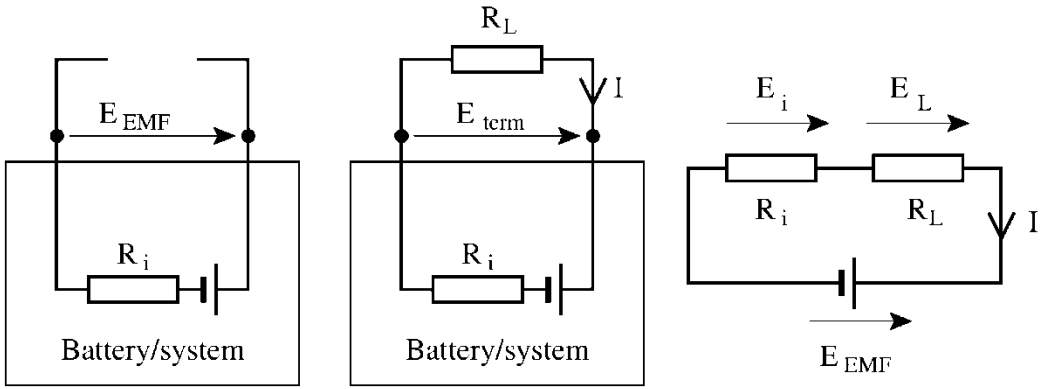
Lecture 6: Conversion efficiency: Batteries



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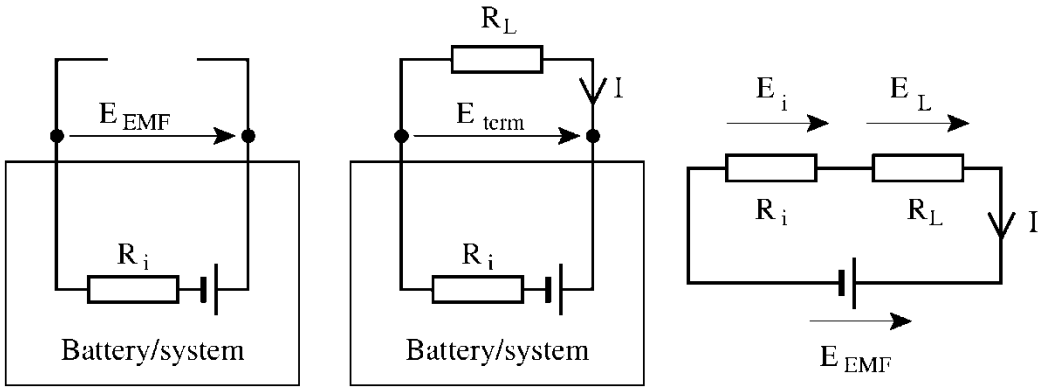
Lecture 6: Conversion efficiency: Batteries



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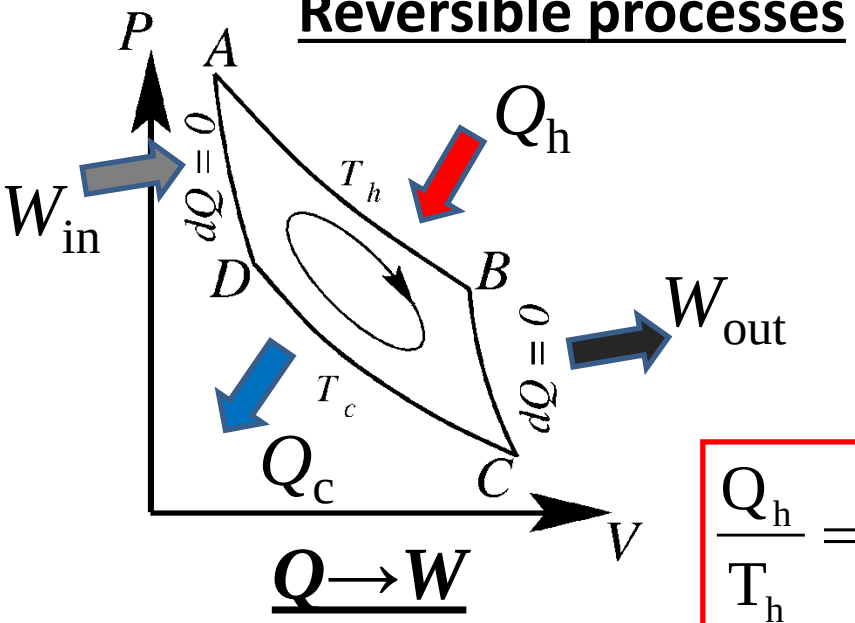
Summary Lecture 6: Efficiency of processes

Summary Lecture 6: Energy conv.: Carnot cycle

Carnot cycle

Reversible processes



Q→W

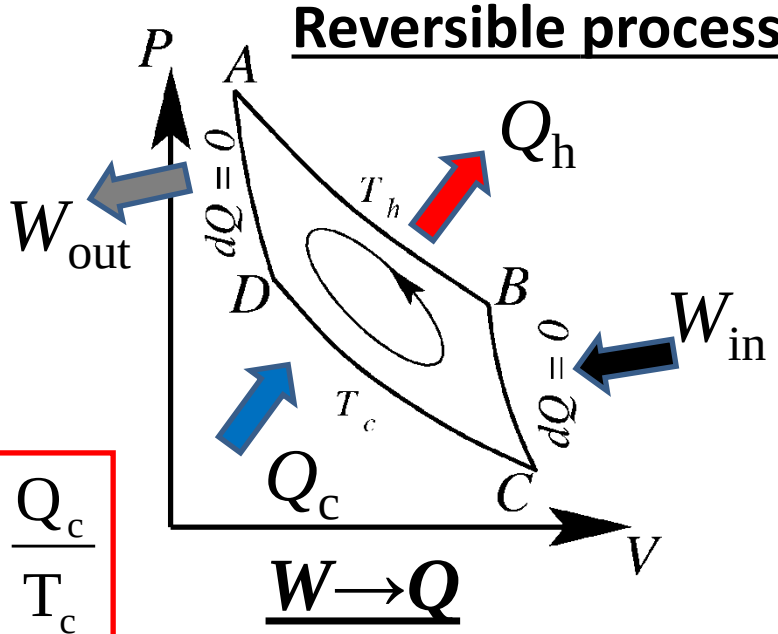
$$\frac{Q_h}{T_h} = -\frac{Q_c}{T_c}$$

$$\eta = 1 - \frac{T_c}{T_h}$$

(heat engine)

Carnot cycle

Reversible processes



W→Q

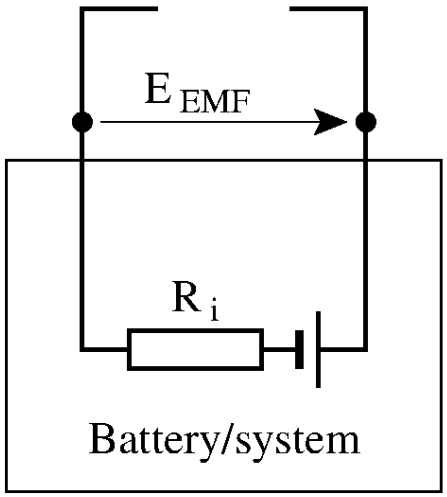
$$\eta \equiv c = \frac{T_c}{T_h - T_c}$$

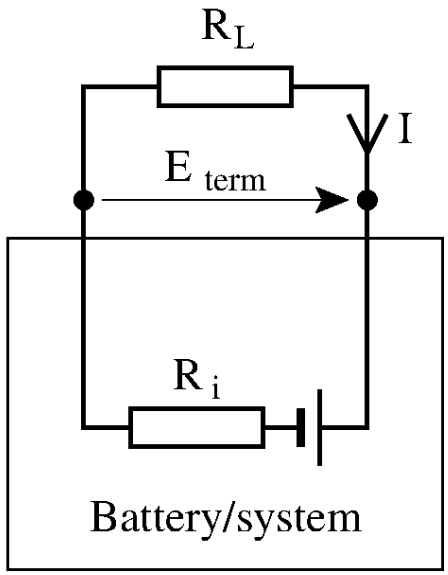
(refrigerator)

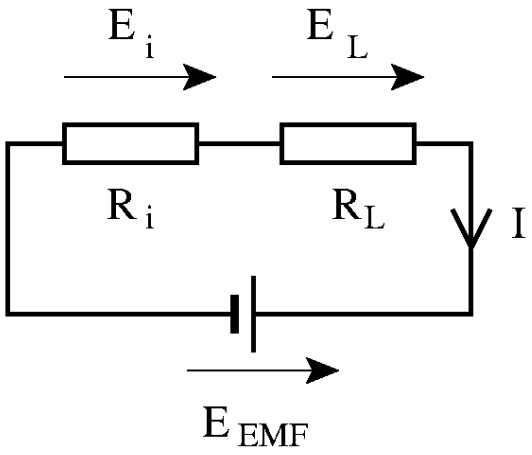
$$\eta \equiv c = \frac{T_h}{T_h - T_c}$$

(heat pump)

Summary Lecture 6: Energy convers.: Batteries







EMF:

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